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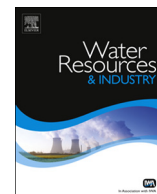
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# The water footprint of electricity in Ecuador: Technology and fuel variation indicate pathways towards water-efficient electricity mixes

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## 1. Introduction

In general, traditional electricity generation in thermal power plants consumes significant volumes of freshwater for the operation, mainly for cooling, and for the fuel life-cycles [1–5]. Electricity generated by renewable sources, e.g., hydropower or biomass-fired thermal power plants, also consumes large amounts of water [6,7], while other renewable sources, e.g., wind or solar have a small water consumption [1]. Electricity generation is expected to grow, while freshwater sources are expected to become scarcer [3,8].

Electricity is not the only consumer of freshwater in a basin. Agriculture, households, and industries also require water. Freshwater availability is limited [9], and the growing demand from all users is the reason why water can become more scarce after the construction of power plants. This constitutes a constraint for electricity production [10].

Existing knowledge about water footprints of electricity includes three clusters of studies. The first cluster has assessed the water requirements of different electricity generation technologies and fuels [1,5,11–14]. They have shown water consumption ranges of some technologies for benchmarking purposes. They have shown that some technologies and fuels are more water-efficient than others. The second cluster includes studies that quantified water consumption for specific technologies to show differences within similar technologies in different regions [6,7,15,16]. They have shown that there are large variations among power plants with similar technologies. These variations are caused by spatial conditions (regional differences) and characteristics of fuel use. However, these two clusters of studies did not address specific electricity technologies (e.g., certain types of run-of-the-river hydropower plants or stationary internal combustion engines) and other fossil fuels besides coal, natural gas, and crude oil (e.g., crude oil derivatives used for electricity generation). Finally, the third cluster includes studies that have used the two previous clusters to define water consumption for energy mixes, including electricity, at the global scale [17–19] or inside a particular boundary [20,21]. They have shown that different mixes implicate different order of magnitude of water consumption. All global studies have used average or median values from the two first clusters which could lead to over- or underestimations of water consumption as it does not consider the large variation among power plants. Therefore, there is a need for a more detailed analysis of the water consumption by power plants that includes a range of electricity generating technologies and fuels showing technologies that are more water-efficient than others, even for technologies that were previously estimated as water-intensive (e.g., hydropower and biomass). Results identify strategies for more water-efficient electricity mixes.

Many studies used the water footprint (WF) tool to quantify water consumption. The WF is a tool that estimate the volume and impacts of freshwater consumed by anthropogenic activities [22,23]. Based on [22], the WF consist of three components: green (precipitation), blue (surface and groundwater) and grey (pollution) WFs.

Ecuador, located at the equator in South America, is suitable as a case study for a research into the WF of various electricity

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generating technologies, because its electricity mix includes a large variety of technologies, including the technologies that were considered water-intensive in previous studies, and it is small enough to permit a detailed assessment of each power plant that contributes to the mix [24]. Ecuador has a large variety of different hydropower technologies (e.g. large, medium, and small-sized, dammed, run-of-the-river (ROR), built-in series, in-conduit and multipurpose technologies), thermal power plant technologies (Rankine, Brayton and Internal combustion engines) with diverse cooling types (wet-tower, once-through and dry cooling), wind and solar power plants. Moreover, Ecuadorian power plants use a large variety of fuels, e.g., crude oil, and its derivatives, natural gas, biogas and biomass (sugarcane bagasse, a residue of the sugar industry) [25].

This paper aims to give blue and green WFs of different types of power plants, including hydropower and thermal power plants, in Ecuador, which is representative of technologies available on a global scale. The four research questions are: i) What are the direct blue and green WFs per power plant technology per unit of electricity ( $\text{m}^3/\text{TJ}_{\text{el}}$ ) in Ecuador? ii) What are the blue and green indirect WFs of the fuels used to operate power plants in Ecuador ( $\text{m}^3/\text{TJ}_{\text{th}}$ )? iii) What is the total blue WF of electricity generation in Ecuador per generating technology ( $\text{m}^3$ )? iv) What are the most water-efficient electricity generating technologies to reduce the blue WF of electricity generation in a country like Ecuador?

For the analysis, the study uses the WF concept. This paper is the first to provide a detailed estimation of WFs of different electricity generation technologies that use a larger range of fuels. Results show ways to make electricity supply more water-efficient.

## 2. Electricity in Ecuador

Ecuador's electricity is generated by different technologies that include several power plants (PPs) types. The technology type defines most of the operation conditions, including water consumption. These technologies are hydropower plants (HPPs), thermal power plants (TPPs), biomass power plants (BPPs), wind power plants, and solar power plants (together denominated as Other Renewables power plants, OPPs).

### 2.1. Ecuadorian electricity mix and its production

Ecuador lies at the equator in South America. The average annual precipitation is 2274 mm; the annual internal renewable water resources (IRWR) are  $442 \text{ km}^3$  [26]. The Andes mountains divide the country into two watersheds, the Amazon and Pacific [27]. Rivers originate in the Andes, flowing either to the Pacific Ocean (west) or to the Atlantic via the Amazon basin (east). The combination of large annual precipitation and the Andes makes Ecuador suitable for HPPs. TPPs function as backup systems for HPPs, as HPPs' production is prioritized over TPPs, and as stand-alone power generators in remote areas, e.g., in the Amazon region generating electricity for the oil industry. BPPs use residues from the sugar industry. OPPs have only started to become part of the national electricity grid recently [28]. In 2017 HPPs produced 72.3 PJ (71% of the electricity in the country), TPPs 26.6 PJ (26%) and BPPs 1.7 PJ (2%). The contribution of OPPs is small, only 0.4 PJ (0.4%). In 2017, only 0.07 PJ were imported from neighboring countries (0.07% of the electricity) [28] so that Ecuador is self-sufficient.

Fig. 1 shows the power plants locations per electricity generating technology (HPPs, TPPs, BPPs, and OPPs, which are solar and wind PPs) in Ecuador, and the location of oil and gas mining, and sugarcane plantations. The HPPs are in the Andes mountains, except for two multipurpose HPPs that are in the western lowlands. TPPs are generally located in the vicinity of oil and gas fields. Solid biomass-fired BPPs are close to the sugarcane fields, biogas-fired BPPs are in cities in the Andes. There is only one wind power plant and some solar power plants in the mountains in the north and the south.

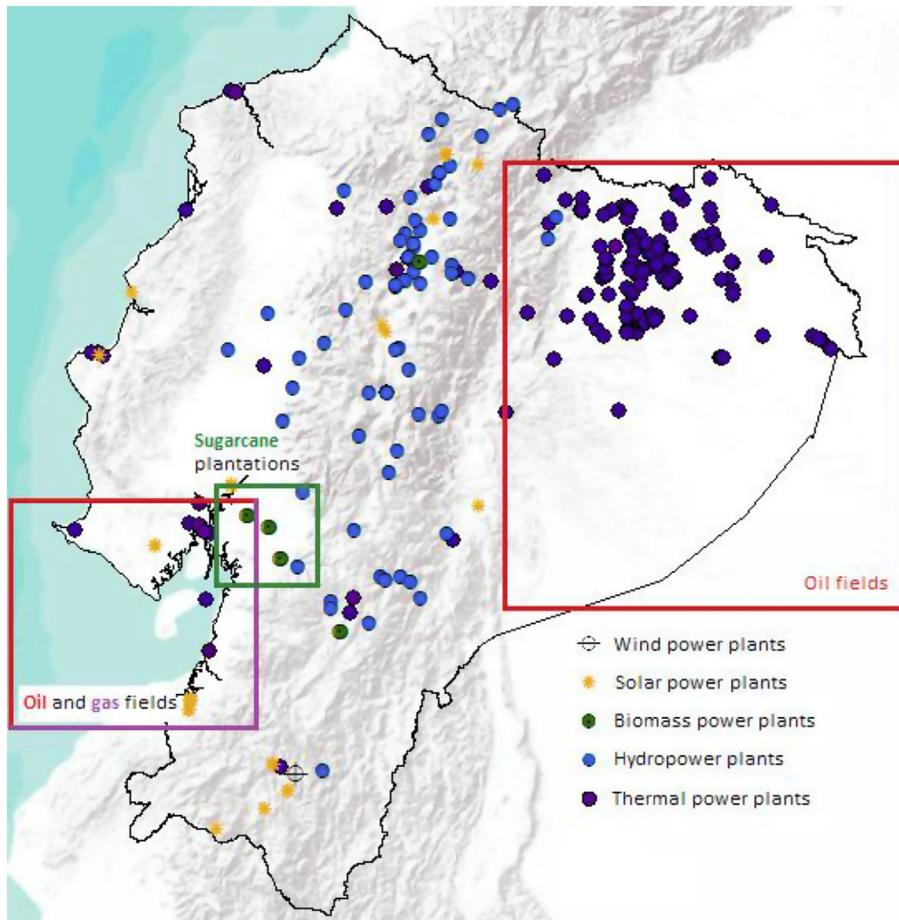
### 2.2. Water consumption characteristics of different electricity generating technologies in Ecuador

The characteristics of the different electricity generating technologies affect their water consumption.

#### 2.2.1. Hydropower plants

HPPs consume water in the form of evaporation from open water surfaces [6]. The evaporation is a function of the evaporation rate and the size of the open water surface. Evaporation depends on climate characteristics, the surface size on the HPP's infrastructure. Typical HPPs include: (i) *dammed* HPPs, (ii) *run-of-the-river* (ROR) HPPs, and (iii) *in-conduit* HPPs that have different characteristics affecting water consumption.

- (i) *Dammed* HPPs have an artificial reservoir formed by a dam [29]. These HPPs include two types based on the shape of their artificial reservoir. The first type includes HPPs with *Flooded Rivers*, in which the dam impounds rivers in narrow passages between mountains, forming an artificial lake along the original river bank. The second type includes HPPs with *Flooded Lakes*, in which a dam impounds rivers in wider and open areas, forming an artificial lake that spreads in all directions along the original river bank. Their open water surfaces are wider and shallower than the ones of the *Flooded River* type. In Ecuador, *Flooded lakes* are usually located high in the mountains and in the valleys; *Flooded rivers* are located in between them. The surface size of artificial reservoirs affects the WF of *dammed* HPPs [15].
- (ii) *Run-of-the-river* (ROR) HPPs do not have a dam, but a construction to deviate the river flow, store water and avoid damage to the turbines [29]. Weirs, sand traps, reservoirs, open canals, charge tanks or surge tanks are examples of the possible infrastructure of ROR HPPs that create open water surfaces, from where water evaporates. ROR HPPs include PPs *with* and *without* reservoirs. ROR HPPs *with* reservoirs are usually larger than RORs *without* reservoirs, have relatively large open water surfaces and water



**Fig. 1.** Location of hydropower plants, thermal power plants, biomass power plants, wind power plants and solar power plants, and oil, gas and sugarcane fields in Ecuador.

losses due to evaporation.

- (iii) In-conduit HPPs take advantage of the water that flows through water supply installations [30], i.e., between storage reservoirs and treatment plants. They generate electricity without the need for infrastructure that generates open water surfaces, and therefore, water is not consumed.

In Ecuador ROR and *dammed* HPPs are sometimes built in a string along a river (*cascaded* HPPs). In this way, electricity generation increases as ROR HPPs benefit from the storage and flow regulation provided by *dammed* HPPs. Moreover, *dammed* HPPs are often part of a multipurpose scheme that is used not only to generate electricity but also for other services as water supply, irrigation and flood control [31].

### 2.3. Thermal power plants

Factors that determine water consumption of TPPs are: (i) the working fluid, (ii) the cooling system [32] and (iii), the fuel.

The working fluid for power generation depends on the TPPs thermodynamic cycle [33]. In Ecuador, TPPs use (i) Rankine, (ii) Brayton and (iii) Internal Combustion Engines (Otto and Diesel) thermodynamic cycles. Rankine PP use steam as a working fluid in a closed-loop cycle, Brayton and Internal Combustion Engines (ICE) PP use an air-fuel mix in an open-loop cycle [33]. Rankine PP consume water when steam losses occur. Brayton and ICE PP have negligible water consumption due to the working fluid.

TPPs' cooling system depends on the thermodynamic cycle and the availability of water. Ecuadorian TPPs use three cooling systems: (i) *wet-tower* cooling, (ii) *once-through* cooling and (iii) *dry cooling*. *Wet-tower* cooling systems use water in a closed-loop cycle, in which a share of the water evaporates [11]. *Once-through* cooling uses an open-loop cycle in which water is diverted from surface water into a heat exchanger and returns to where it came from with a higher temperature [2]. These systems use fresh, or saline water [34]. *Dry cooling* systems use refrigerant-based cooling fluids in a closed-loop cycle where flowing air removes waste heat. This system does not use water. In Ecuador, some ICE PP use this cooling technology. TPPs use cooling for different functions. Rankine PP cool the working fluid [33,35], ICE PP cool the engine [33], while Brayton PP do not require cooling.

The fuel used by TPPs also affects water consumption. Ecuador does not have exploitable coal or natural gas resources, and no nuclear plants, but it has oil [36]. Most of TPPs use crude oil and oil derivatives [25] like fuel oil, diesel, naphtha, LPG and residue oil [37]. Crude oil, residue oil, and fuel oil are highly viscous and require fuel *preheating systems* to store and transport the oil. These systems are: i) *water-based* systems, which use steam, or ii) *oil-based* systems, which use thermal oil. The first system consumes water as steam production has losses. The second system's water requirement is negligible. Moreover, diesel combustion in Brayton turbines generates NOx [38]. To reduce emissions, Ecuadorian Brayton TPPs using diesel have a GHG control system using water to mix with the fumes [39].

#### 2.4. Biomass power plants

Biomass power plants (BPPs) are TPPs using biomass as fuel. Water consumption of BPPs depends on the type of fuel and the thermodynamic cycle in which the power plant operates. Ecuadorian BPPs use two biomass types: (i) solid biomass from sugarcane bagasse (a residue of the sugar industry), and (ii) biogas (mostly methane) from the waste decomposition of municipal landfills. Bagasse-fired BPPs are subsidiaries of companies whose main economic activity is sugar production. BPPs burn solid biomass in Rankine PPs that use wet-tower cooling systems [40]. They operate five months per year, from May to November, when bagasse in the sugarcane harvesting period is available [41,42]. Biogas-fired BPPs are subsidiaries of municipal waste-disposal companies. BPPs burn biogas in ICE PPs that are usually dry cooled [43].

#### 2.5. Wind and solar power plants

Solar power plant's water consumption depends on the PP's type. There are two types of solar power plants i) photovoltaic systems (PVs) and ii) Concentrated Solar Power thermal systems (CSPs) with different water consumption. PVs only use water for cleaning purposes, while CSPs use a Rankine thermodynamic cycle that requires water as any other Rankine TPP [11]. Ecuador only has PVs. Historically, solar and wind power plants were stand-alone systems. Recently they have started to become part of the national electricity grid [28]. Previous studies have shown that these two technologies have such small water consumptions that they are practically negligible [1,18].

### 3. Method

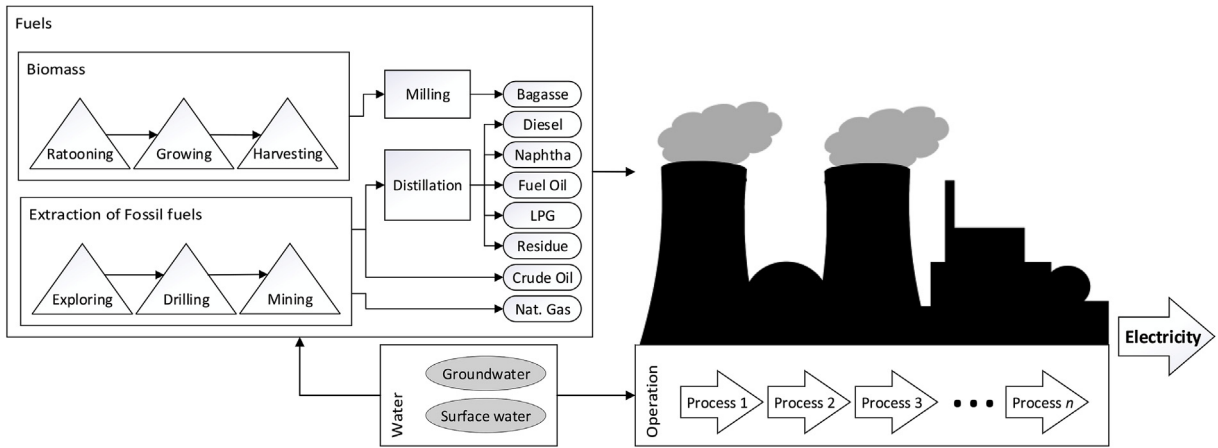
The water footprint (WF) is a tool that estimates the volume of freshwater consumed by anthropogenic activities. Two methods exist for quantifying water consumption: The WF method (as described in Ref. [22]), and the ISO method (as described in Ref. [23]). The main difference between methods is observed in the *Impact Assessment* stage. However, they follow a similar life cycle approach for the *quantification/inventory* stage [44,45]. In this paper we address the *quantification/inventory* stage only, so any of the two could be used. We chose to use the method described in Ref. [22]. The assessment of water consumption of a product, good or service using the WF is defined as a water footprint assessment (WFA) [22]. The WF consist of three components: green, blue and grey WFs. The green WF considers the consumption of green water sources (precipitation), the blue WF refers to the consumption of ground and surface water (freshwater) and the grey WF refers to pollution and is defined as the volume of freshwater required to assimilate pollutants into freshwater bodies to reach accepted water quality standards [22]. This study included green, and blue WFs and excluded grey WFs, and non-freshwater sources.

The WF of a power plant includes a direct WF and an indirect WF. The direct WF is the blue water needed for the operations of the power plant itself. The indirect WF considers the construction and decommissioning of the plant and the fuels' life cycle. Several studies [1,18,46] have shown that construction and decommissioning of power plants have insignificant WFs when compared to the direct WF for HPPs, TPPs, and BPPs. For PVs, the indirect WF is small and for wind PPs is negligible [1]. Therefore, we excluded WFs related to construction and decommissioning. The indirect WF related to the fuels life cycle includes four stages: (i) exploration (crop growth in the case of biomass); (ii) fuel mining (harvesting in the case of biomass); (iii) fuel transport and (iv) fuel processing. The WF of the transport stage is negligible compared to the WF of the rest of the fuel's life cycle [1]. Moreover, in Ecuador, power plants are located near the fuel mining locations and processing factories, with small transport distances (Fig. 1). Thus, we assumed that the transport WF is negligible.

Fig. 2 shows the stages of the indirect and direct WF components for the assessment of the WF of electricity in Ecuador. The indirect WF includes the water evaporated, incorporated or lost during the life-cycle production of the fuels. The direct WF includes the freshwater consumed during electricity generation. For biomass, the life-cycle considers ratooning (or seeding), growing, harvesting and sugarcane milling. Sugar cane is a perennial crop. After harvesting, the stem base and roots are left on the field to grow again in the next growing period of 5–6 months [42]. The residue bagasse is used as fuel by BPPs. For fossil fuels, primary sources (natural gas and crude oil [25]) are extracted (wells are explored, drilled and mined). A few power plants use the primary sources without further processing, but most plants use derived fuel products of the crude oil distillation.

We calculated the green and blue WFs associated with the operation per Ecuadorian power plant applying the WF calculation method as given in Ref. [22]. The assessment included three clusters: (i) inventory of the current composition of the Ecuadorian electricity mix and related water consumption, (ii) assessment of blue and green fuel WFs, (iii) assessment of blue WFs of electricity generating technologies. The clusters include a series of calculation steps (31). The most relevant steps (16) are given below, while [Appendix A](#) gives all calculation steps. Fig. 3 shows the steps of the second and third clusters and how they relate to each other.





**Fig. 2.** Stages included in the indirect and direct WFs for Ecuadorian power plants. The indirect WF includes the water evaporated, incorporated or lost during the life-cycle production of the fuels. The direct WF includes the freshwater consumed during the electricity generation. For biomass, the life-cycle considers ratooning, growing, harvesting and milling of sugarcane. The residue bagasse is used as fuel by biomass power plants. For fossil fuels, primary sources (natural gas and crude oil) are extracted (wells are explored, drilled and mined). A few power plants use the primary sources without further processing, but most of them use derived fuels product of the crude oil distillation.

### 3.1. The composition of the ecuadorian electricity mix

#### 3.1.1. Inventory of ecuadorian power plants

**Step 1** makes an inventory of Ecuadorian power plants in 2017 and their operating characteristics. Data were derived from Ref. [28].

#### 3.1.2. Classification of power plants

Previous studies have aggregated power plants into categories according to their operating conditions and types of fuels used. Gleick [5], Macknick et al. [11], Meldrum et al. [1] and Mekonnen et al. [18] first categorized PPs based on their energy source, introducing subcategories according to specific characteristics (e.g., fuel mining, preparation technologies, cooling types). We expanded the categories including classes and subclasses based on water consumption characteristics described in Subsection 2.2. **Step 2** classifies the Ecuadorian power plants into four categories, ten classes, and eleven subclasses.

The four categories were based on the energy source: HPPs, TPPs (which include power plants that use natural gas, oil, and its derivatives), BPPs and OPPs (which include solar and wind power plants). HPPs include three classes: *dammed* HPPs, *ROR* HPPs, and *In-conduit* HPPs. *Dammed* and *ROR* HPPs both have two subclasses: the *flooded lake* (HFL) and *flooded river* (HFR) for *dammed* HPPs, and the *reservoir* (HRR) and *no reservoir* (HNR) subclass for *ROR* HPPs. *In-conduit* HPPs were not subclassified, because they do not have open water surfaces and no blue WF. TPPs include three classes: the *Rankine*, *Brayton* and *ICE* PPs class. The *Rankine* and *Brayton* class include two subclasses: the *wet-tower* (RWT) and *once-through* (ROT) cooling subclass for *Rankine* PPs, and the *diesel* and *gas-fired* class for *Brayton* PPs. ICEs include three subclasses: i) *wet-tower* (IWT) cooling, ii) *once-through* (IOT) cooling and iii) *dry* (IDC) cooling. BPPs include two classes: solid biomass-fired power plants (BSB) and biogas-fired power plants. In Ecuador, solid biomass-fired power plants use sugarcane bagasse as fuel. Biogas-fired BPPs' direct blue WF is negligible, so they were not considered in this study. Finally, OPPs include solar and wind power plants, which were excluded as they have negligible direct and indirect WFs and because their electricity generation in Ecuador is relatively small compared to other generating technologies. Fig. 4 shows the classification scheme of Ecuadorian power plants.

For the classification, we derived power plant characteristics from national databases [28,47] and sources that give information per power plant. When the HPP type or TPP cooling system could not be identified, we used Google Maps® and Bing Maps® aerial images to identify infrastructure using the method described in Ref. [32] and TPPs cooling systems. Appendix B gives the power plants classes and subclasses and the references used.

### 3.2. The fuels' water footprint of ecuadorian power plants

#### 3.2.1. Natural gas, crude oil, and oil derivatives

Ecuador has natural gas fields. Data on water requirements for natural gas extraction are available from Ref. [1]. We assumed that the indirect blue WF for natural gas of  $4.21 \text{ m}^3/\text{TJ}_{\text{th}}$  related to extraction is representative for all blue WFs of natural gas in Ecuador.

For crude oil and derivatives, **Step 3** calculates the blue WF of crude oil extraction from Ecuadorian wells,  $WF_{\text{Ex}}$  ( $\text{m}^3/\text{m}_{\text{oil}}^3$ ), as the sum of the blue WF for oil well exploration and drilling,  $WF_{\text{E\&D}}$  ( $\text{m}^3/\text{m}_{\text{oil}}^3$ ), and the blue WF of oil mining,  $WF_{\text{M}}$  ( $\text{m}^3/\text{m}_{\text{oil}}^3$ ) as:

$$WF_{\text{Ex}} = WF_{\text{E\&D}} + WF_{\text{M}} \quad (1)$$

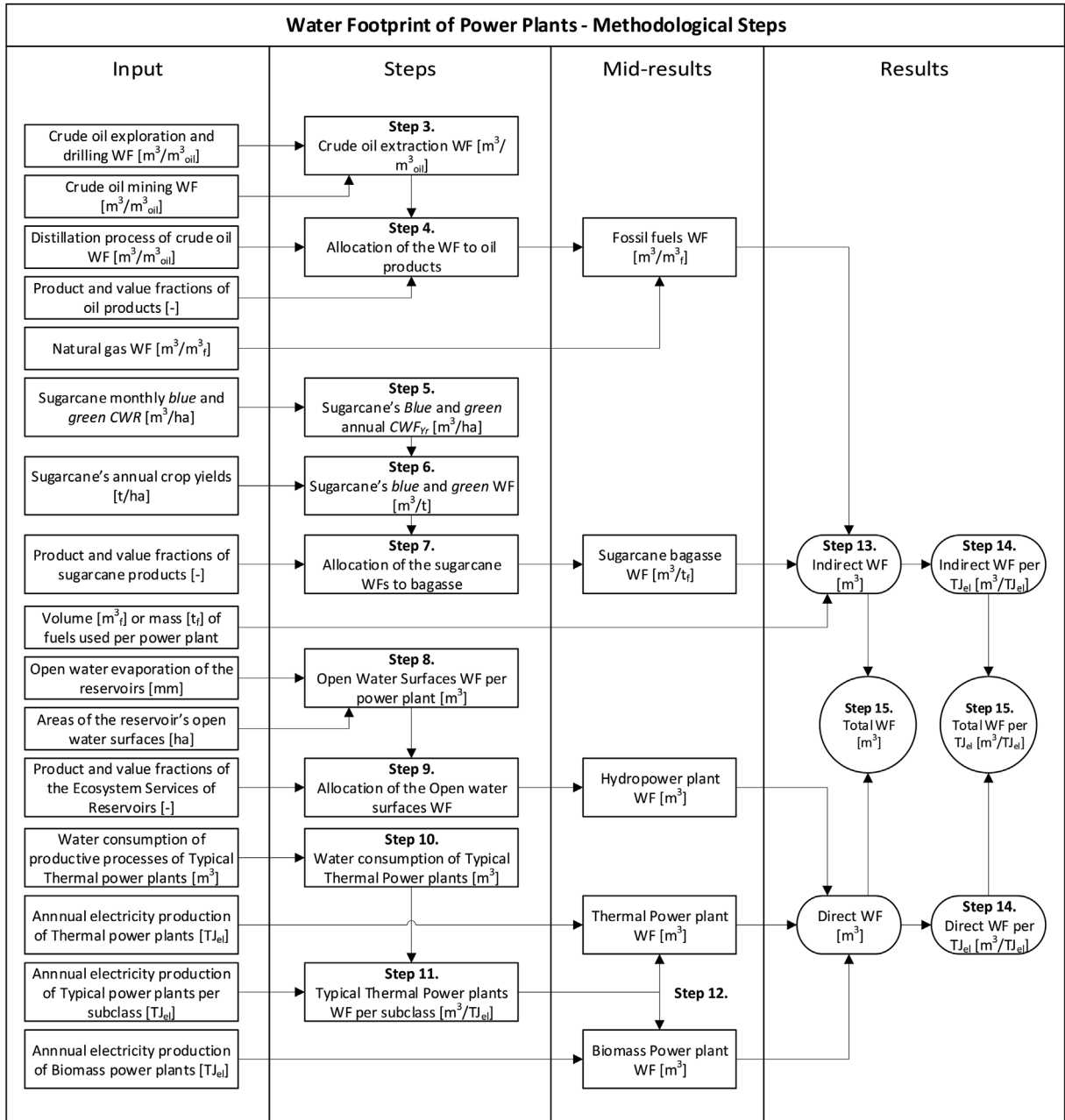
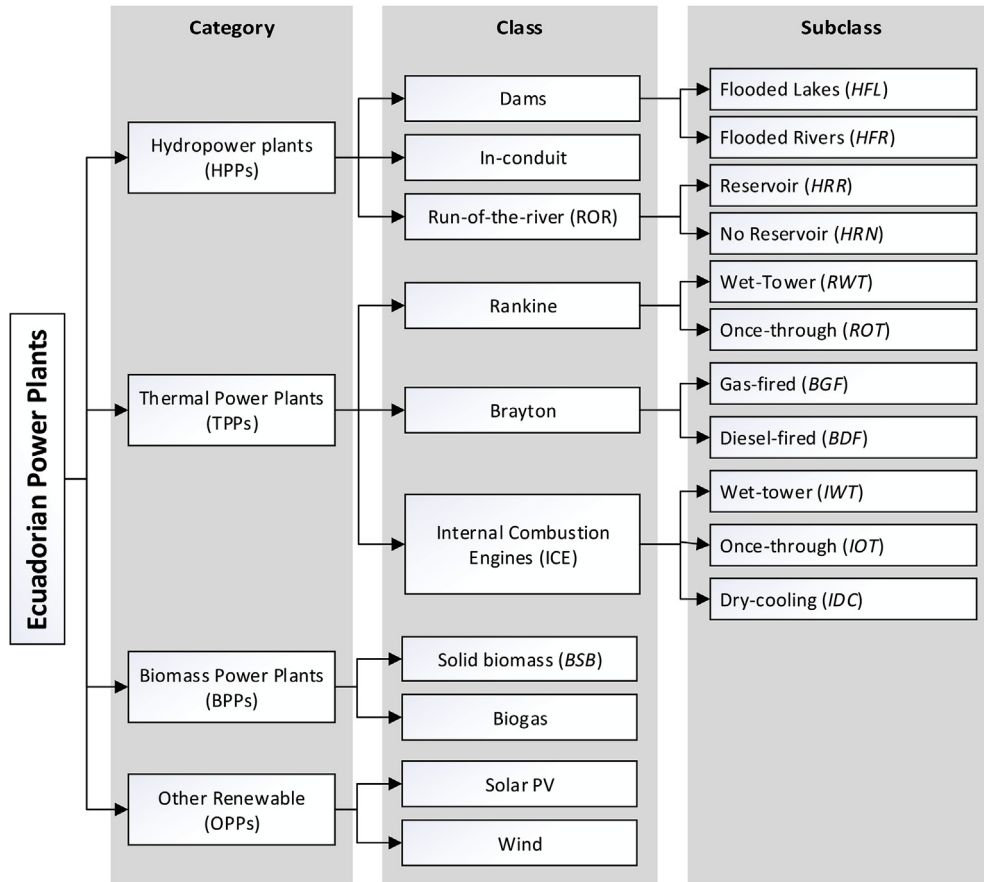


Fig. 3. Scheme with the steps followed in this study for the estimation of the WF of power plants in Ecuador.

Ecuadorian oil has a high viscosity [48], requiring enhanced oil recovery methods (EOR) to facilitate extraction. We calculated the  $WF_{E \& D}$  ( $\text{m}^3/\text{m}^3_{\text{oil}}$ ) based on the average freshwater consumption per well,  $WF_{\text{well}}$  ( $\text{m}^3/\text{well}$ ), and the relation between the number of oil wells explored and drilled,  $N_{\text{wells}}$ , and the annual oil production,  $P$  ( $\text{m}^3_{\text{oil}}$ ). Data on well numbers and annual oil production were derived from the national oil trading company Petroecuador EP [49], data on average water consumption per well was derived from the national oil extraction company Petroamazonas EP [50]. For the  $WF_M$  we derived data from Ref. [51] of  $2.97 \text{ m}^3/\text{m}^3_{\text{oil}}$ , considering an EOR of steam injection that reuses 71% of the process water. Appendix A gives the calculation of  $WF_{E \& D}$ . Distillation produces several derivatives. Step 4 estimates blue WFs of crude oil derivatives used for electricity generation in Ecuador. We allocated the blue WF of crude oil to each derivative  $d$  using the *Stepwise Accumulative Approach* as defined in Hoekstra et al. [22]. First, we calculated the product fraction,  $f_p[d]$ , and value fraction,  $f_v[d]$ , of the oil distillation products as:

$$f_p[d] = \frac{w[d]}{w[i]} \quad (2)$$



**Fig. 4.** Classification of Ecuadorian power plants into four categories based on the energy source: Hydropower plants (HPPs), Thermal power plants (TPPs), Biomass power plants (BPPs) and Other Renewable Power plants (OPPs). The HPPs were classified into three classes and four subclasses. First based on the characteristics of their open water surfaces in *dams*, *run-of-the-river (ROR)* and *in-conduit*, and secondly on the shape and size of their open water surfaces: for *dammed* HPPs into *Flooded Lakes (HFL)* and *Flooded Rivers (HFR)*, and for *ROR* HPPs into power plants *with reservoirs (HRR)* and *without reservoirs (HNR)*. TPPs were classified into three classes and seven subclasses based on their water consumption. First by their thermodynamic cycle in *Rankine*, *Brayton* and *Internal Combustion Engines (ICE)*. *Rankine* and *ICE* were subclassified according to their cooling systems into *wet-tower (RWT and IWT respectively)*, *once-through (ROT and IOT respectively)* and *dry cooling* (the latter only for *ICE, IDC*). Their fuel subclassified *Brayton* power plants into *diesel-fired* and *gas-fired*. BPPs were divided into two classes regarding the state in which the biomass is used: *solid biomass* and *biogas*. Finally, OPPs (solar and wind) were joined together in a category.

$$f_v[d] = \frac{u_p[d] * w[d]}{\sum_{d=1}^k (u_p[d] * w[d])} \quad (3)$$

where  $f_p[d]$  is the fraction of derivative  $d$  processed from input product  $i$ . It is the ratio of the weight ( $w[d]$ ) of derivative  $d$  and the weight ( $w[i]$ ) of input product  $i$ .  $f_v[d]$  is the fraction of the market value of derivative  $d$  to the aggregated market value of all derivatives ( $d = 1$  to  $k$ ) obtained from the input products  $i$ . The market value is the multiplication of the market price of derivative ( $d$ ) ( $u_p[d]$ ) to the  $w[d]$ . Data on Ecuadorian oil derivatives for 2013 were taken from Ref. [48]. We assumed that there is no significant annual variation in the distillation process and crude oil properties remain constant. [Appendix A](#) gives the price, energy content, product and value fractions for oil distillation products for the Esmeraldas refinery in 2013. Next, we allocated the blue WF to each product  $d$  of the crude oil distillation as:

$$WF_f[d] = \left( \frac{WF_{process}[i]}{f_p[d, i]} + \sum_{i=1}^y \frac{WF_{product}[i]}{f_p[d, i]} \right) * f_v[d] \quad (4)$$

where the process WF is given per unit of input product  $i$  divided by the product fraction of that input product ( $f_p[d, i]$ ). The second part of equation (4) calculates the sum of the blue WF of the input products  $i$ , divided by the product fraction of those input products. In this case, there is only one product WF (crude oil,  $WF_{Ex}$ ) and the process WF is the distillation blue WF ( $WF_p$ ), which we calculated based on the average water consumption rate of the distillation process and the average oil distillation rate over the period of 2010–2016. Data for the Esmeraldas refinery were taken from Refs. [49,52]. We assumed that the other Ecuadorian refineries (two



smaller ones) have similar WFs. [Appendix A](#) gives the  $WF_p$  calculation.

### 3.2.2. Sugarcane and bagasse

For the calculation of the green and blue WF of sugar cane bagasse, we used the method described in Ref. [7]. Sugarcane blue WFs,  $blue\ WF_{SC}$  ( $m^3/t$ ), and green WFs,  $green\ WF_{SC}$  ( $m^3/t$ ), are calculated using annual blue and green crop water requirements (blue and green  $CWR_{yr}$ ) as:

$$\begin{aligned} blue\ WF_{SC} &= \frac{blue\ CWR_{yr}}{Y_{SC}} \\ green\ WF_{SC} &= \frac{green\ CWR_{yr}}{Y_{SC}} \end{aligned} \quad (5)$$

where,  $Y_{SC}$  is the average annual sugar cane yield ( $t/ha$ ). Data on yields of sugarcane producing bagasse for electricity were derived from Refs. [53–60]. [Appendix C](#) gives the annual yields for the different sugarcane fields. **Step 5** calculates the sugarcane blue and green  $CWR_{yr}$ , ( $m^3/ha$ ), producing bagasse for electricity in Ecuador, as:

$$\begin{aligned} blue\ CWR_{yr} &= \sum_{m=1}^{12} blue\ CWR[m] \\ green\ CWR_{yr} &= \sum_{m=1}^{12} green\ CWR[m] \end{aligned} \quad (6)$$

where,  $blue\ CWR[m]$  is the blue component of the monthly CWR of month  $m$  and  $green\ CWR[m]$  is the green component of the monthly CWR of month  $m$  ( $m^3/ha$ ). The CWR includes a blue and green CWR as sometimes the crop water requirement is fulfilled with a mix of rainfall and irrigation. In Ecuador, bagasse for electricity originates from irrigated sugarcane. When rainfall is not enough, irrigation is applied as sugar cane companies use hydrological models to estimate the appropriate CWRs to improve yields [61]. The assessment of blue and green CWRs was done by assessing the contribution of precipitation to total CWRs. If monthly precipitation is larger or equals CWRs, we assumed the blue CWR is zero. When precipitation is smaller, the blue CWR is the additional water provided to the crop. Usually, during the wet season (November to April) rainfall is enough for CWRs, and little or no irrigation is needed. During the dry season (May to October) irrigation is needed. We assessed monthly blue and green CWRs because the seasonal variation of water availability influences the ratio of blue and green components. The calculation of the blue and green  $CWR[m]$  is based on the crop's daily evapotranspiration ( $ET_c$ ). [Appendix A](#) gives the calculation. **Step 6** calculates the blue and green  $WF_{SC}$  of sugarcane using equation (5).

Sugarcane is the primary source of different products and by-products (sugar, molasses, and bagasse). **Step 7** allocates the WF to bagasse based on the product and value fractions using equations (2)–(4) in a similar way as **Step 4**. The product fractions were taken from Ref. [62] and the unitary prices from Ref. [63]. BBPs only use bagasse and no other residues like leaves or stems. [Appendix A](#) gives products and byproducts of sugarcane production, including product fractions and unitary prices.

## 3.3. Assessment of the blue water footprint of electricity generating technologies in Ecuador

### 3.3.1. WFs of hydropower plants

The blue WF of HPPs is determined by the evaporation from their open water surfaces. **Step 8** calculates this evaporation,  $WF_{OWS}[p]$  per hydropower plant  $p$  ( $m^3$ ), using the gross method described by Ref. [6] as:

$$WF_{OWS}[p] = \sum_{r=1}^R (10 \cdot Ev[r] \cdot A_R[r]) \quad (7)$$

where,  $Ev[r]$  is the annual evaporation (mm) of open water surface  $r$ . The factor 10 is used to convert mm to  $m^3/ha$ , and  $A_R[r]$  is the area of the open water surface  $r$  (ha). A HPP  $p$  can have one or more open water surfaces depending on their infrastructure. The  $WF_{OWS}[p]$  was calculated as the sum of the evaporation from those open water surfaces (from  $r = 1$  to  $R$ ). The  $Ev[r]$  was calculated based on meteorological data using the Modified Penman Method as described by Ref. [64] as it is suitable for equatorial regions [46]. Meteorological data were derived from the National Meteorological Agency (INAMHI) [65] and the Ecuadorian Solar Atlas [66]. The  $A_R[r]$  was estimated using geo-referencing and Geographic Information Software (GIS) and topographic and bathymetric maps. Polygons per open water surface  $r$ , were generated and measured. Maps of the Ecuadorian terrain were derived from Ref. [67]. [Appendix A](#) gives the description of the calculation of  $Ev[r]$  and  $A_R[r]$ . [Appendix D](#) gives the location of the HPPs, the area of their open water surfaces and the nearby meteorological station from which data were taken for the evaporation calculation.

**Step 9** calculates the direct blue WF,  $WF_{dir}[p]$  in  $m^3$ , of the hydropower plant  $p$  based on the whether their open water surfaces are shared or not. Usually, in Ecuador, the open water surfaces of power plant  $p$  are only used by that HPP. In this case, the  $WF_{dir}[p]$  is the same as the evaporation from the OWS. However, some HPPs' open water surfaces are shared with more than one power plant (power plants in cascade), or they also serve for other ecological services (multipurpose reservoirs). For both cases, we calculated the  $WF_{dir}[p]$  using the approach defined by Refs. [15,68] as follows:

$$WF_{dir}[p] = WF_{OWS}[p] * \eta \quad (8)$$

where,  $\eta$  is the allocation factor. Equation (8) refers to the *Stepwise Accumulative Approach* described in **Step 4**, when the  $WF_{process}[i]$  is zero, the product fraction ( $f_p$ ) is equal to 1 and the value fraction ( $f_v$ ) changes to the allocation factor  $\eta$ . This is the case for HPPs as there is no consumption during the electricity production inside the HPPs.

Multipurpose reservoirs could have a few potential ecosystem services, such as electricity generation, water supply, flood control, irrigation, recreation, aquaculture, or conservation. However, Ecuadorian multipurpose reservoirs considered in this study have been designed only for electricity generation, water supply, flood control, irrigation. For HPPs with *multipurpose* open water surfaces, the allocation factor is defined as the ratio between the economic values of hydroelectricity and the economic value of the sum of the ecosystem services in the reservoir. For HPPs in *cascade*, the allocation factor  $\eta$  is defined as the ratio of the electricity generation of the HPP  $p$  and the total electricity production of the power plants in the string, considering that all HPPs in the string receive the same price per unit of electricity generated.

**Appendix A** gives the calculation of the allocation factor. **Appendix E** shows the allocation calculation of the cases of multipurpose and cascaded HPPs.

### 3.3.2. WFs of thermal and biomass power plants

Data on water consumption of TPPs in Ecuador are scarce and available for a few PPs. To assess the WFs of TPPs in Ecuador, we defined *typical power plants*, which are the PPs with available data of water consumption. We assumed that these water consumption data were representative for all TPPs inside each subclass of TPPs. **Appendix F** gives a list of *typical power plants* per TPP subclass, the data sources, and their timeframe.

**Step 10** calculates the annual water consumption of typical TPPs,  $WF_{dir}[t]$  ( $m^3$ ) by summing the average water consumption  $W_{Proc}[k]$  per operational process  $k$  (from 1 to  $a$ ) for the PP (e.g., water filtering, demineralization, cooling) as:

$$WF_{dir}[t] = \sum_{k=1}^a W_{Proc}[k] \quad (9)$$

**Appendix F** gives water consumption and characteristics per typical thermal power plant.

**Step 11** calculates the direct blue WF per unit of energy,  $WF_{Edir}[t, s]$  ( $m^3/TJ$ ), of a typical TPP  $t$  per subclass  $s$  by dividing the  $WF_{dir}[t]$  by the average annual electricity output over the period 1999-2017,  $E[t]$  (TJ):

$$WF_{Edir}[t, s] = \frac{WF_{dir}[t]}{E[t]} \quad (10)$$

We assumed that typical power plants are representative for the entire subclass  $s$ .

**Step 12** calculates the direct blue WF of the rest of the TPPs,  $WF_{dir}[p, s]$  ( $m^3$ ), by multiplying the annual average electricity output per TPP over the period 1999-2017,  $E[p]$  (TJ), by the direct blue WF per unit of energy,  $WF_{Edir}[t, s]$ :

$$WF_{dir}[p, s] = E[p] * WF_{Edir}[t, s] \quad (11)$$

BPPs operate like Rankine wet-tower power plants. We used the average monthly direct blue WF per unit of energy,  $WF_{Edir}[t, s]$ , of Wet-tower (RWT) power plants to calculate the BPPs direct blue WF,  $WF_{dir}[p, s]$ .

### 3.3.3. Blue WFs per power plant, subclass, and category

**Step 13** calculates the indirect blue WF,  $WF_{ind}[p]$  ( $m^3$ ), per power plant  $p$  (TPPs and BPPs only as HPPs do not have indirect WF). It was defined as the sum of the blue WFs of the fuels used by the PP (from  $f = 1$  to  $F$ ), which was calculated by multiplying the blue WF of fuel  $d$ ,  $WF_f[d]$  ( $m^3/m^3$ ), (or  $m^3/t_f$  for biomass) by the average of the total volume (or mass for biomass) of that fuel consumed over the period 1999-2017,  $V[d]$  ( $m^3$  or  $t_f$ ) as follows:

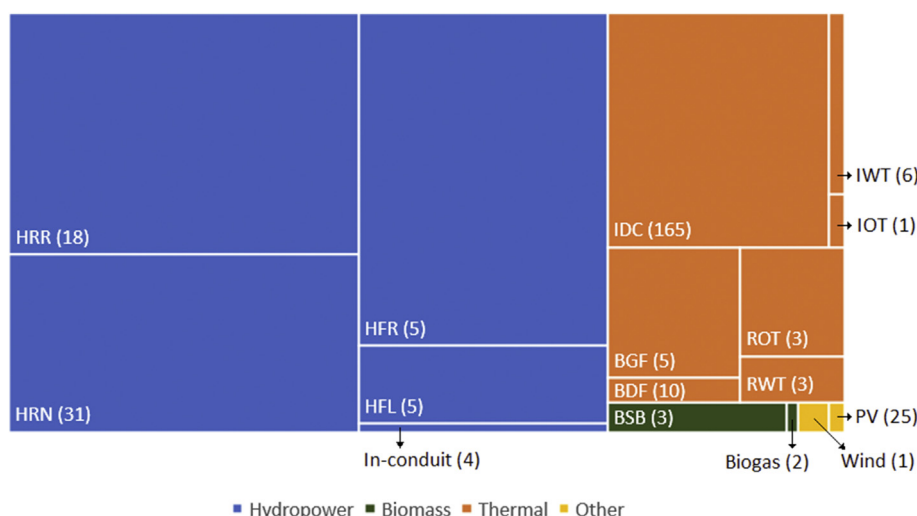
$$WF_{ind}[p] = \sum_{f=1}^F (V[d] * WF_f[d])[p] \quad (12)$$

Data on fuel consumption were derived from Ref. [28].

**Step 14** calculates the annual direct WF,  $WF_{Edir}[p]$ , and indirect WF,  $WF_{Eind}[p]$ , per unit of electricity generated ( $m^3/TJ_{el}$ ) per power plant  $p$ , by dividing the direct and indirect WFs to its average annual electricity output,  $E[p]$  ( $TJ_{el}$ ), over the period 1999-2017. Data on electricity generation were derived from Ref. [28].

**Step 15** calculates the total blue WF,  $WF[p]$  ( $m^3$ ), for power plant  $p$  as the sum of the  $WF_{ind}[p]$  and the  $WF_{dir}[p]$  of power plant  $p$ . In a similar way, the total WF per unit of electricity generated of power plant  $p$ ,  $WF_E[p]$  in  $m^3/TJ_{el}$ , is the sum of the  $WF_{Edir}[p]$ , and  $WF_{Eind}[p]$ .

**Step 16** calculates the blue WF per subclass and category. The subclasses blue WF,  $WF[s]$  ( $m^3$ ), is calculated by summing all the power plants  $WF[p]$  per subclass  $s$ . The categories blue WF,  $WF[c]$  ( $m^3$ ), is calculated in the same way. The WF per unit of electricity per subclass is expressed as a range showing the smallest and largest  $WF_{Etot}[p, s]$ , as well as the median value.



**Fig. 5.** Power plants per category and subclass and contribution to electricity generation in Ecuador in 2017. For hydropower five subclasses are shown: run-of-the-river with reservoirs (HRR), run-of-the-river without reservoirs (HNR), dammed Flooded rivers (HFR), dammed Flooded lakes (HFL) and in-conduit. For thermal power plants, seven subclasses are shown: Rankine wet-tower (RWT), Rankine once-through (ROT), Brayton diesel-fired (BDF), Brayton gas-fired (BGF), Internal combustion engines (ICE) dry cooled (IDC), ICE wet-tower and ICE once-through. For biomass, there are two classes: Solid biomass and biogas. For the Other renewables category, two subclasses are shown: wind power plants and solar photovoltaic power plants.

## 4. Results

### 4.1. Ecuadorian power plant technologies and their contribution to the gross electricity production of the country

Fig. 5 shows the number of PPs per subclass, class, and category and their contribution to the national electricity output of Ecuador in 2017. There were 287 PPs in operation. Most PPs (165) belong to the TPPs' IDC subclass. They generate 15% of the electricity or 64 times more than IOTs, which produce 7% of ROT, and 19 times more than IWTs, which produce 60% of RWT. In the other TPPs subclasses, BGF electricity output is five times larger than the BDF output and ROTs generate twice as much as RWTs. For hydropower, the HFR and HFL subclasses both have five PPs, but HFRs produce more than four times as much electricity than HFLs. Of the 49 ROR PPs, the 31 HNRs generate 26% of the electricity generated by 18 HRRs. Fig. 5 shows that in-conduit, biogas, wind, and solar PV PPs include 32 PPs, but only generate 1% of the electricity in Ecuador.

### 4.2. Water footprints of fuels used in ecuadorian power plants

#### 4.2.1. Blue water footprints of crude oil and its derived fuels

The average exploration and drilling blue WF of crude oil is 0.02 cubic meter of water per cubic meter of fuel ( $\text{m}^3/\text{m}_f^3$ ). The distillation blue WF is  $0.71 \text{ m}^3/\text{m}_f^3$ . Both footprints are smaller than the blue WF for the mining of crude oil of  $2.98 \text{ m}^3/\text{m}_f^3$ . Table 1 gives the blue WFs of crude oil and its derived fuels used for electricity generation per unit of volume ( $\text{m}^3/\text{m}_f^3$ ) and unit of energy ( $\text{m}^3/\text{TJ}_{\text{th}}$ ).

Table 1 shows that the difference between the fuel with the largest blue WF per unit of volume (diesel 2 with  $2.9 \text{ m}^3/\text{m}_f^3$ ) and the

**Table 1**

Blue water footprint per volume of fuel ( $\text{m}^3/\text{m}_f^3$ ) and unit of energy ( $\text{m}^3/\text{TJ}_{\text{th}}$ ) of crude oil and its derived fuels used for electricity generation.

Fuel	Blue WF	
	$[\text{m}^3/\text{m}_f^3]$	$[\text{m}^3/\text{TJ}_{\text{th}}]$
Crude Oil <sup>a</sup>	3.00	83.5
Diesel 2	2.90	79.4
Naphtha	2.36	73.3
Fuel Oil	1.73	46.0
Residue	1.33	36.4
LPG	1.07	43.9

<sup>a</sup> Crude oil is the primary source for the derived fuels. Some power plants use it as fuel before the distillation process.

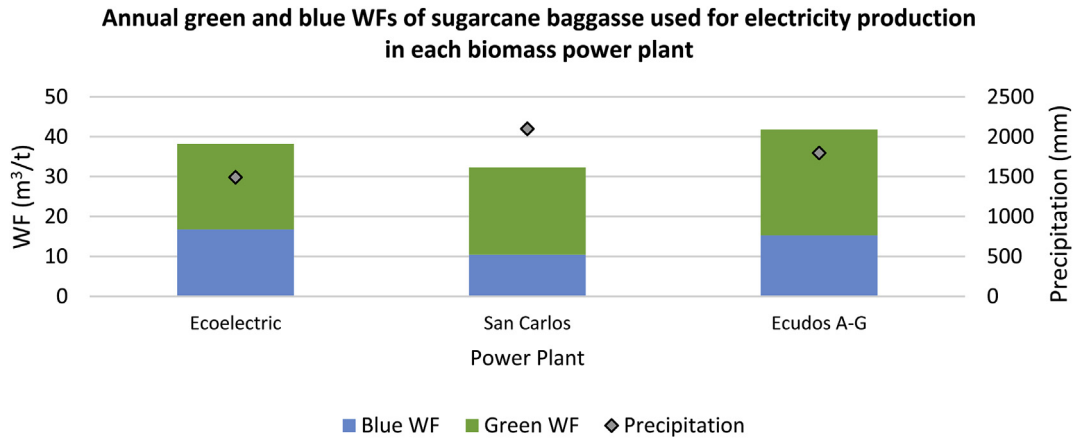


Fig. 6. Green and blue WFs of sugarcane bagasse used for electricity generation in each biomass power plant in Ecuador ( $\text{m}^3/\text{t}$ ), and annual cumulative precipitation in the sugarcane fields of those power plants (mm).

smallest WF (LPG with  $1.07 \text{ m}^3/\text{m}^3$ ) is almost threefold. WFs of naphtha, fuel oil and residue range in between these values. The same order is observed for the WF per unit of energy, except for LPG, which has a larger WF than residue, because LPG has a smaller energy content per unit of volume than residue ( $0.024 \text{ TJ}/\text{m}^3$  and  $0.037 \text{ TJ}/\text{m}^3$  respectively).

#### 4.2.2. Green and blue water footprints of sugarcane bagasse

Fig. 6 shows the average green and blue WFs of bagasse used for electricity generation between 1990 and 2012 for three power plants and the average annual precipitation per location. The WF varies in volume and color due to differences in local crop yields and rainfall patterns [42].

In Ecuador, bagasse used for electricity generation has an average total blue and green WF of  $37 \text{ m}^3/\text{t}$  and  $4911 \text{ m}^3/\text{TJ}_h$ . The green WF is  $23 \text{ m}^3/\text{t}$  and the blue WF  $14 \text{ m}^3/\text{t}$ . Fig. 6 also shows that the San Carlos power plant has a smaller blue WF and higher precipitation, so there is little need for irrigation. Appendix A gives the precipitation data of the sugarcane fields that provide bagasse for the three BPPs, and the monthly blue and green CWR of Ecuadorian sugarcane.

#### 4.2.3. Blue water footprint of electricity generating technologies in Ecuador

Table 2 shows the annual indirect, direct and total blue WFs of electricity from 1999 to 2017 for the subclasses of the three categories of power plants (HPPs, BPPs and TPPs). Appendix G gives the blue WF of individual Ecuadorian power plants. Table 2 shows large variation among the blue WF of Ecuadorian power plants: first in terms of the differences between categories, second in terms of the differences between subclasses that are part of the same class, and finally in terms of the variation inside each subclass.

Firstly, there is a large blue WF variation among subclasses of different categories. BPPs have the largest median blue WF,  $18069 \text{ m}^3/\text{TJ}_e$ , almost five times larger than the median blue WF of electricity from the HFL subclass. The latter is the subclass with the largest blue WF of the HPPs category, almost five times larger than the blue WF of the IWT subclass, the subclass with the largest blue WF of the TPPs category. These variations are caused by large differences in operation conditions. For instance, BPPs have larger blue WFs because they combine a large direct blue WF for wet-tower cooling and a large indirect blue WF because they use bagasse from irrigated sugar cane.

Secondly, Table 2 shows that there is large variation among subclasses in the same category. In the TPP category, the IWTs' median blue WF is almost 16 times larger than the smallest blue WF of the BGF subclass. This difference correlates to the significant variation of the direct blue WF per cooling type. Wet-tower subclasses (RWT and IWT) have the largest WF because their cooling system is water intensive. ROTs and IOTs do not use freshwater for cooling, but they have a blue WF because most of them use heavy fuels that require an additional preheating system consuming water. RWTs and IWTs have an average direct blue WF 15 times larger than the direct blue WF of ROTs and IOTs and 72 times larger than IDCs, the most water-efficient cooling technology. Moreover, HPPs show the largest WF variation inside a category because HPPs' WFs are determined by the volume of water that evaporates from the HPP open water surfaces, and the four HPPs subclasses have large differences in the volumes of water evaporating from their open water surfaces. For instance, the HFLs' median blue WFs is around 48 times larger than the median blue WF of the smallest HPPs subclass (HRR) as larger volumes of water evaporate from HFL than for HRR. HPPs' WFs are determined by the water volume that evaporates from the HPP open water surfaces where evaporation is a function of: i) the size of the open water surfaces and ii) the evaporation rates determined by climatic conditions. Fig. 7a and b shows to which extent these two factors affect the blue WF of HPPs.

Fig. 7a shows a linear relationship between open water surfaces and blue WFs. As the area of the open water surface increases, so does the blue WF. The outliers of this trend correspond to ROR HPPs that benefit from upstream reservoirs, so they have small open water surfaces, but relatively large blue WFs due to the allocation of the evaporation from the reservoirs upstream. The subclasses cluster in groups from smaller open water surfaces (HNR) to larger surfaces (HFL). HRRs and HFRs are in between these two

**Table 2**

Annual indirect, direct and total blue water footprints of electricity ( $\text{m}^3/\text{TJ}_{\text{el}}$ ) for three categories of electricity generation: 1) Hydropower (dams and run-of-the-river (ROR)), 2) Biomass (solid biomass), and 3) Thermal power plants (Rankine, Brayton, and internal combustion engines).

Category	Class	Subclass	$\text{m}^3/\text{TJ}_{\text{el}}$			
			Indirect	Direct	Total	Median
Hydropower plants	Dam	Flooded Lake	-	1254–13085	1254–13085	3828
		Flooded River	-	19–868	19–868	276
	ROR <sup>a</sup>	Reservoir	-	27–3975	27–3975	79
		No Reservoir	-	14–1078	14–1078	216
Biomass power plants	Solid		13931–25728	623–649	14557–26377	18069
Thermal power plants	Rankine cycle	Wet-tower <sup>b</sup>	113–334	292–689	473–936	802
		Once-through <sup>c</sup>	113–134	0–31	113–176	165
	Brayton cycle <sup>d</sup>	Diesel-fired <sup>e</sup>	218–541	45–111	264–652	354
		Gas-fired	16–117	0	16–117	54
	Internal Combustion Engines <sup>f</sup>	Wet-tower <sup>g</sup>	51–115	741–744	792–859	844
		Once-through <sup>h</sup>	122	111	233	233
		Dry cooling <sup>i</sup>	9–565	0–66	9–565	184

<sup>a</sup> Run-of-the-river (ROR) hydropower plants.

<sup>b</sup> Rankine power plants with wet-tower cooling use fuel oil, residue, crude oil (which require preheating) and diesel 2 (no preheating required).

<sup>c</sup> Brayton power plants with once-through cooling are fuel oil-fired, which requires preheating.

<sup>d</sup> Brayton cycle power plants do not have a cooling system as their working fluid (gas) is in an open loop.

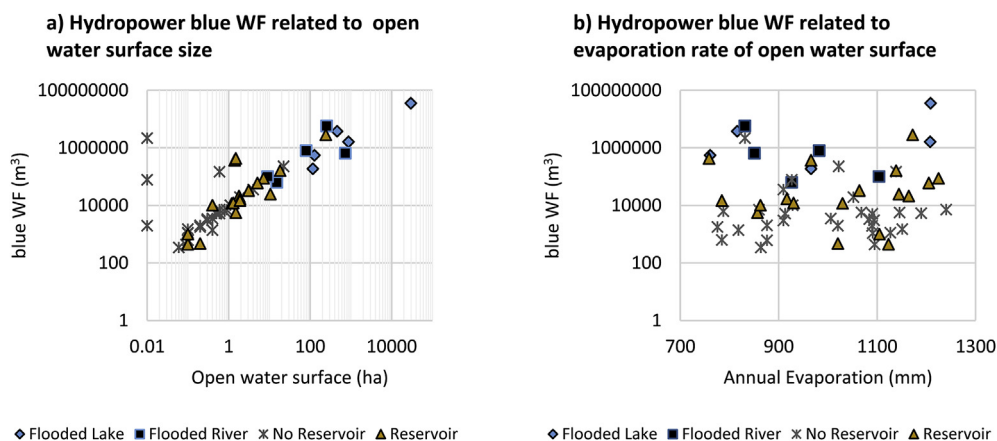
<sup>e</sup> Diesel-fired Brayton power plants use water to comply with GHG emissions. The fumes produced in the combustion chamber by burning diesel are emulsified with water to reduce NOx.

<sup>f</sup> Internal Combustion Engines (ICE) refer to Diesel cycle and Otto cycle stationary engines that generate electricity. This class uses a different cooling system to cool the engine and not the working fluid.

<sup>g</sup> ICE with a wet-tower cooling system use steam to preheat the fuel, which is highly viscous (fuel oil, crude oil or residue).

<sup>h</sup> ICE with a once-through cooling system does not consume water for this purpose, but they consume it to preheat the fuel oil.

<sup>i</sup> ICE with dry cooling use radiators in a closed-loop cooling system that usually works with water-based refrigerant that requires practically zero replenishment water. Some of these power plants require fuels (Fuel oil, Residue and Crude oil) to preheat, but most of them do not require it as they use Diesel 2.

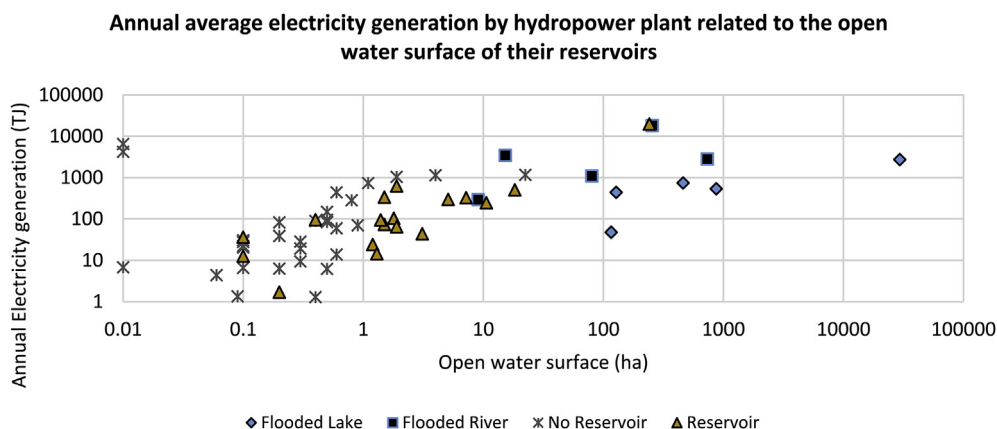


**Fig. 7.** a-b. Variation of the blue WF of hydropower plants. a) blue WF of hydropower plants compared to the total area of their open water surfaces subject to evaporation (Note: both axes are logarithmic). b) blue WF of hydropower plants compared to the evaporation rate of their open water surfaces (Note: vertical axis is logarithmic). Power plants grouped according to their power plants' subclasses (2 subclasses for dammed hydropower plants: flooded lakes and flooded rivers and two subclasses for ROR hydropower plants: ROR with reservoirs and without reservoirs).

subclasses. Fig. 7b shows that in Ecuador the evaporation rate does not have a significant correlation with the blue WF. HPP subclasses do not show an increasing or decreasing pattern. This suggests that the size of the open water surfaces has a larger effect on the blue WF of the HPPs than the evaporation rate of the reservoir. This is probably due to the country's equatorial climate and the HPP locations in the Andes mountains.

Fig. 8 shows the relation between annual average electricity generation (TJ) and the open water surface of the Ecuadorian HPPs reservoirs. The outliers correspond to the ROR HPPs that benefit from the reservoirs of other HPPs upstream. Fig. 8 shows that for ROR HPPs, the larger the open water surface, the larger the annual electricity generation, independently of the subclass. In this way, they can produce large amounts of electricity with significantly smaller sizes of their open water surfaces. However, Fig. 8 also shows a difference between the trend of dammed HPPs and its subclasses. HFLs HPPs have large open water surfaces and lower electricity production than their HFR counterparts. Table 2, Figs. 7 and 8 indicate that the large WF differences of HPPs are caused by





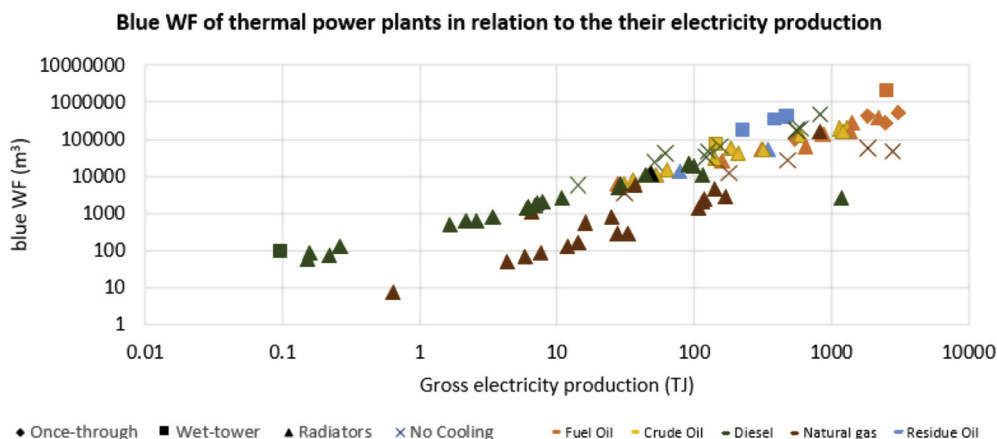
**Fig. 8.** The relation between annual average electricity generation, in TJ, and the open water surface of the reservoirs of Ecuadorian hydropower plants. Power plants grouped according to their power plants' subclasses (2 subclasses for dammed hydropower plants: flooded lakes and flooded rivers and two subclasses for ROR hydropower plants: ROR with reservoirs and without reservoirs). (Note: logarithmic scales).

differences among their infrastructure. The smallest blue WFs are observed for HPPs that benefit from infrastructure with small and deep open water surfaces producing relatively large amounts of electricity (e.g., *HFRs*), or for medium and small-sized HPPs that do not require large open water surfaces (e.g., *HRRs*).

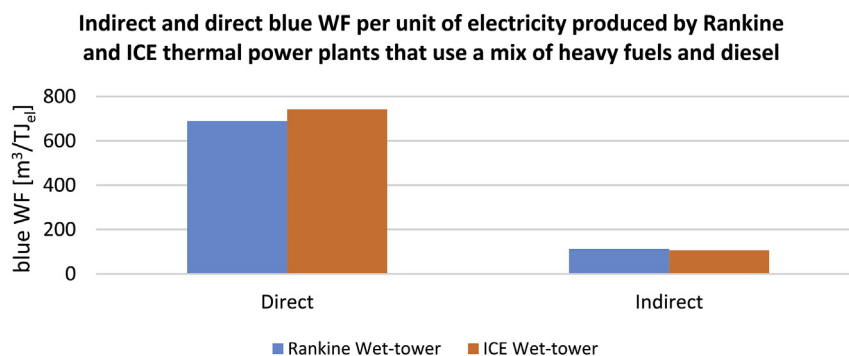
Finally, Table 2 shows that there is large variation inside each subclass. These differences are due to the unique operating conditions of each power plant inside each subclass. For example, the difference between HPPs with the smallest and largest blue WF in the *HRR* subclass is almost 250 fold. Similar differences are observed in the *HFR* and *HNR* subclasses (109 fold and 108 fold respectively). In this case too, the variation of blue WF for *HRR*, *HFR* and *HNR* happens because each PP inside those subclasses has different infrastructure. For BPPs, the variation within the *BSB* class is caused by the sugarcane bagasse used. The bagasse has different WFs depending on the site where the sugarcane is grown (Fig. 6). Weather conditions of sugarcane fields define when and how much the crop needs to be irrigated during the dry season. This correlates to the variation among *BSB* indirect blue WFs.

There are also large differences in TPPs subclasses. The largest difference between the TPP with the smallest and largest blue WF is observed in the *IDC* subclass (63 fold), and it is mainly due to the differences in the fuel use. The lowest end of this subclass uses diesel 2, and the highest end of the range uses a mix of diesel 2 and heavy fuels (crude oil, residue oil, and fuel oil). Fig. 9 shows blue WF variation ( $\text{m}^3$ ) of TPPs in relation to their electricity production. The TPPs have been grouped first in terms of their cooling system (once-through, wet-tower, dry cooling, no cooling), next by the fuel used (fuel oil, residue oil, crude oil, diesel, and natural gas) showing the significant differences between cooling systems. TPPs with wet-tower cooling (squares) have the largest blue WF in relation to their electricity production. The TPPs with the lowest blue WF in relation to their electricity production are a group of TPPs with dry cooling. Moreover, Fig. 9 shows the difference between fuels used by the TPPs and their blue WF. Natural gas-fired TPPs (brown) have the smallest blue WF per TJ of electricity. Crude oil (yellow), fuel oil (orange) and diesel (green) using plants have WFs between plants using residue oil (blue) and gas. The WF variation for TPP subclasses is mainly correlated with the specific fuel mix applied. For example, in Table 2 the *BGF* subclass has a large blue WF variation. They mostly consume natural gas, but one plant in the *BGF* subclass uses diesel, resulting in seven times larger blue WF compared to the other *BGF* plants.

The fuel mix also affects the WFs of Rankine and ICE TPPs that use heavy fuels (crude oil, residue oil, and fuel oil). The use of



**Fig. 9.** Blue WF ( $\text{m}^3$ ) of thermal power plants in relation to gross electricity generation (TJ) per fuel type. (Note: logarithmic scales).

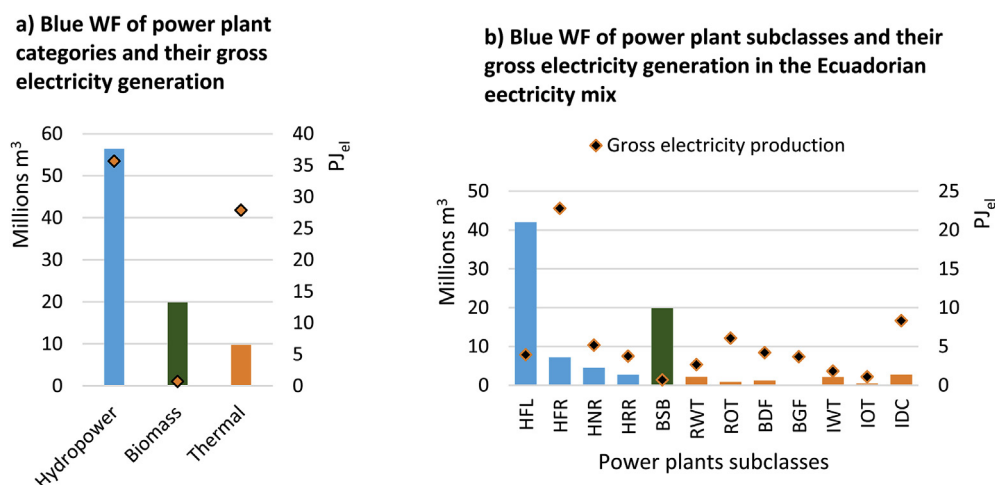


**Fig. 10.** Indirect and direct blue WF per unit of electricity of thermal power plants (Rankine wet-tower and Internal combustion Engines (ICE) Wet-tower subclasses) that use a mix of heavy fuels (crude oil, residue oil or fuel oil) and diesel.

heavy fuels also includes diesel 2 consumption. The volume of diesel 2 in the fuel mix of the TPP affects the relation between direct and indirect WF of the TPPs. Fig. 10 shows the indirect and direct blue WF per unit of electricity of the typical power TPPs that use a mix of heavy fuels and diesel of two comparable subclasses (RWT and IWT as they have similar cooling systems). It shows that the addition of diesel 2 has a larger effect on the increase of the direct blue WF than in the decrease of indirect blue WF.

#### 4.3. Blue water footprint of the current ecuadorian electricity mix

Fig. 11a and b shows the composition of the blue WF of electricity in Ecuador. Fig. 11a shows blue WFs per power plant category (HPPs, BPPs and TPPs) compared to the gross electricity output; Fig. 11b shows blue WFs and gross electricity output per PP subclass. Fig. 11a shows that TPPs have the smallest contribution to the total Ecuadorian blue WF for electricity (11%), followed by BPPs (24%) and HPPs (65%). When comparing the blue WF of power plant categories and their gross electricity output (Fig. 11a), the blue WF does not linearly relate to the amount of electricity generated. From 1999 to 2017, TPPs produced 41% of the electricity, but the contribution to the blue WF was relatively small. BPPs electricity generation is small compared to HPPs or TPPs (only 1%), but they have the second largest blue WF after hydropower. Fig. 11b shows that subclasses with large blue WFs are not necessarily the ones with large electricity output. For instance, HFLs have the largest blue WF, six times larger than HFRs WFs, but they only generate one-fourth of their electricity. RWTs and IWTs contribute 44% to the blue WF of the TPP category but generate 8% of the category's electricity.



**Fig. 11.** a-b. The composition of the blue WF of electricity generation in Ecuador (total of 86.8 million m³). a) Blue WF and gross electricity generation of three power plants categories in the country's (hydropower, biomass, and thermal power plants), and b) Blue WF and gross electricity output per power plant subclasses: four subclasses for hydropower (dammed flooded lakes (HFL), flooded rivers (HFR), run-of-the-river (ROR) with reservoirs (HRR) and without reservoirs (HNR)), one class for biomass power plants (solid biomass (BSB)), and seven subclasses for Thermal power plants (Rankine wet-tower (RWT) and once-through (ROT), Brayton diesel- (BDF) and gas-fired (BGF); and Internal Combustion Engines (ICE) wet-tower (IWT), once-through (IOT) and dry-cooled (IDC)).

## 5. Discussion

### 5.1. Implications for the water-electricity nexus

Previous studies have focused on assessing the most evident water-intensive electricity generating technologies, like HPPs with large reservoirs (*HFL* in our classification), biomass-fired and water-cooled TPPs [6,7,12,13,16,69]. Our study assessed WFs of these technologies in more detail. For instance, we also assessed TPPs operational WFs (besides cooling) for fuel use and GHG control. The studies of Meldrum et al. [1], Mekonnen and Hoekstra [6], and Gleick [5] have shown large WF variations for power plant categories. By including more technologies per category, we show that there are large differences among WFs in subclasses of electricity generating technologies. The variation of the blue WFs of PPs is large, as reported in previous studies, but the order of magnitude varies between subclasses. For instance, we found that for HPPs, *HFLs* have the largest blue WF per unit of electricity generated, followed by *HFRs*, *HNRs* and finally the smallest blue WF for *HRRs*. These differences have not been reported in previous studies.

Additionally, we assessed the WF of two electricity generating technologies for which no WF data were available, ROR HPPs and ICE PPs, and included WFs of HPPs with open water surfaces smaller than 0.1 ha. We show that water that evaporates from ROR HPPs' open water surfaces (weirs, sand traps and reservoirs) is significant in relation to their electricity output. Small ROR HPPs, therefore, have a comparable blue WF per unit of electricity ( $\text{m}^3/\text{TJ}_{\text{el}}$ ) as HPPs with large open water surfaces. The linear relationship between water evaporation and electricity output of small ROR HPPs is the reason that we advise that small ROR HPPs should be included in future WFAs of electricity. ICE TPPs indirect blue WF is the largest of all technologies, but they are usually water-efficient when combined with dry cooling (radiators).

Mekonnen and Hoekstra [70] calculated an average annual blue WF of 2443 million  $\text{m}^3$  for the productive sectors of Ecuador (agriculture, livestock, industry, and domestic water supply) between 1996 and 2005. Our results show that Ecuadorian electricity generation consumes 86.5 million  $\text{m}^3$  of water yearly, or 3.5% of the total blue WF, which is small in comparison to the 2186 million  $\text{m}^3$  of freshwater consumed yearly for crop production and livestock water supply [70] in the country. The small contribution indicates that electricity generation does not have a significant impact on the country's total WF and that its optimization has limited impact on the country's freshwater consumption. If there are always plenty resources in the country for all users, then the optimization of a water-efficient mix for Ecuador is not relevant for the country itself but might provide insights towards the more efficient use of water for electricity, especially for other countries with different conditions and resources. Nonetheless, this remains to be defined in a more detailed study that considers the spatial and temporal constraints of freshwater in the country's basins and the competition between users.

### 5.2. Influential factors of the WF of electricity generating technologies

Our results show a large variation of direct and indirect blue WFs between different electricity generating technologies affected by several factors. For *BSB* BPPs, sugarcane irrigation is the most influential factor. Also, regional differences in precipitation patterns affect blue WFs of *BSB* BPPs. Wetter regions could have lower blue WFs than the ones described in this study.

For HPPs, blue WFs are mainly determined by their open water surfaces size and not by evaporation rates due to the equatorial climate. Further studies are required to assess this relationship for higher latitudes. Dammed HPPs with small and deep reservoirs (*HFR*) are more water-efficient than dammed HPPs with large and shallow reservoirs (*HFL*), mainly because *HFRs* produce more electricity with smaller open water surfaces than *HFLs*. ROR HPPs have relatively large blue WFs in *HRR*, but this permits them to produce more electricity, which results in relatively small blue WFs per unit of electricity compared to WFs of RORs without reservoirs (*HNR*). Although *HNRs* have relatively small open water surfaces, their blue WFs are comparable to *HFRs*, or larger than *HRR* WFs. The most water-efficient HPPs technologies are *HFR* and *HRR*, and they should be prioritized.

For TPPs, the cooling system is the most influential factor affecting blue WFs. TPPs with water-intensive cooling systems, like wet-tower cooling, have the largest blue WF of the category. Brayton cycle TPPs, which do not require cooling, have the smallest blue WF. However, the TPPs fuel use also has a large impact. There is a large difference between Brayton subclasses and IDC TPPs due to different fuel use. Brayton and ICE power plants using natural gas have smaller blue WFs than Diesel-fired Brayton and ICE PPs. TPPs using heavy fuel oils (crude oil, residue oil, and fuel oil) have larger WFs than their counterparts because of the additional requirement of having a fuel preheating system that usually is steam-based, and the addition of diesel 2 into the fuel mix. The volume of diesel 2 in relation to the heavy fuel required in these TPPs is also an influential factor for TPPs, especially for the direct WF. On the one hand, diesel 2 has a small share in the fuel mix of Rankine TPPs (*RWT*). In these TPPs, diesel 2 is only used to start the boiler, and then heavy oil is burnt alone for the rest of the operation. On the other hand, diesel 2 has a larger share in the fuel mix of ICEs (*IWT*). They mix diesel 2 with heavy fuels throughout the operation of the TPP. The direct blue WF of *IWTs* is larger than the direct blue WF of *RWT* because *IWT* only need to produce steam for the fuel's preheating system, and this implicates larger blue WF than in the case of *RWT* that already produce steam for its thermodynamic cycle and can divert part of it to the preheating system.

### 5.3. Limitations of the study

Lack of data gave rise to the following assumptions: i) We used available data on oil extraction and distillation from a state-owned company assuming their WFs are representative for the sector. There are 17 oil extracting companies [71], but only one, Petroamazonas EP, a company producing 71% of Ecuador's oil, provides data on water consumption for operations. In Ecuador, there are three refineries, but only one, the Esmeraldas refinery, which produces half of the Ecuadorian oil derivatives [49], provides data on

water consumption for operations. We assumed the WF data are representative for the other two refineries. ii) We did not calculate the direct WF of all TPPs and BPPs, because data for each power plant were not available. We categorized TPPs and BPPs into classes and subclasses with similar operating conditions and assumed that WFs of typical power plants (that had data) were representative. This assumption did not influence the results of the country's blue WF, because the direct WFs of TPPs and BPPs is relatively small in comparison to their indirect blue WF. iii) When available we used multiannual monthly water consumption averages to assess the multiannual average blue WF of power plants. However, multiannual averages do not always cover the same period due to lack of data. For example, we used the period 1999–2017 to calculate the average power plant electricity generation and fuel consumption, and the period 1981–2010 for meteorological data. We assumed that these averages are representative of the processes and operations and that the Ecuadorian climate does not have large annual variation.

Moreover, we excluded the gray WF. For some power plant subclasses, the gray WFs could be large in comparison to green or blue WFs (i.e., for thermal power plants with once-through cooling causing thermal water pollution). If also gray WFs are considered, the country's total electricity WF is larger, and some subclasses have larger WFs than the ones presented in this paper.

#### 5.4. Comparison of results with previous studies

There are fuel blue WFs available from the literature. Gerbens-Leenes et al. [72] have calculated a blue WF range for diesel of 28–376 m<sup>3</sup>/TJ<sub>th</sub> and for heavy fuel oil of 10–133 m<sup>3</sup>/TJ<sub>th</sub>. Our results are 79 and 46 m<sup>3</sup>/TJ<sub>th</sub> respectively, which are in the range found by Gerbens-Leenes et al. For sugarcane bagasse, Mathioudakis et al. [13] have calculated a blue WF of 20 m<sup>3</sup>/t, using data from Ref. [73]. Our monthly average blue WF is 15 m<sup>3</sup>/t, 25% smaller than the blue WF assessed by Mathioudakis et al. that was based on global average blue WFs of sugar cane, including countries with relatively small yields. Our smaller WF is probably caused by the relatively large sugarcane yield in Ecuador that is 20% larger than the country's average yield reported by FAO [74].

Previous studies have shown that HPPs have large blue WFs, but differences are large and depend on local circumstances, i.e., on the size of the open water surfaces and local climate. Differences can be four orders of magnitude. Mekonnen and Hoekstra [6] have shown that the average global WF of hydropower ranges between 39000 and 69400 m<sup>3</sup>/TJ<sub>el</sub>, Liu et al. [15] have calculated a WF for hydropower in China between 3900 and 100000 m<sup>3</sup>/TJ<sub>el</sub>, and Zhao and Liu [68] have calculated a range between 800 and 9200 m<sup>3</sup>/TJ<sub>el</sub> for HPPs with multipurpose reservoirs. Our calculations give a blue WF from 14 to 13085 m<sup>3</sup>/TJ<sub>el</sub>, with a median WF of 197 m<sup>3</sup>/TJ<sub>el</sub>, which are smaller than the WFs reported previously. Earlier studies, however, only included large HPPs (*HFL* category), while this study also included small HPPs. When only comparing *HFL*'s WFs, our results range from 1254 to 13085 m<sup>3</sup>/TJ<sub>el</sub> similar to results of Zhao and Liu [68]. Mathioudakis et al. [13] have calculated a blue WF of electricity from sugarcane bagasse of 9100 m<sup>3</sup>/TJ<sub>el</sub>. Our calculations give a median blue WF of 18069 m<sup>3</sup>/TJ<sub>el</sub>, almost twice the WF of Mathioudakis et al. [13]. This difference is likely to result from the differences between sugarcane bagasse's higher heating values (HHV). Ecuadorian sugarcane has an HHV of 7.6 MJ/kg [75], which is almost half the HHV value used by Mathioudakis et al. [13] who used the average of a large range of HHVs reported for case studies around the world. The Ecuadorian sugarcane HHV is relatively small compared to the HHVs of those case studies. Mekonnen et al. [18] and Meldrum et al. [1] have shown that the direct blue WFs of coal-fired power plants range between 61 and 1410 m<sup>3</sup>/TJ<sub>el</sub>. For *RWT* class TPPs, with similar cooling systems, the median blue direct WF is 802 m<sup>3</sup>/TJ<sub>el</sub>, comparable to earlier results. Meldrum et al. [1] give a WF of 52.3 m<sup>3</sup>/TJ<sub>el</sub> for coal-fired power plants with open loop cooling. This study calculated a median blue WF of a *ROT* power plant of 176 m<sup>3</sup>/TJ<sub>el</sub>, three times larger than the value obtained by Meldrum et al. [1]. Ecuadorian *ROT* power plants use steam to preheat the fuel oil before burning, generating a relatively large WF. Our result for *BGF* power plants median blue WFs (54 m<sup>3</sup>/TJ<sub>el</sub>) is comparable to the WF of gas combustion turbines of 52.7 m<sup>3</sup>/TJ<sub>el</sub> reported by Meldrum et al. [1]. Ecuadorian *BDF* power plants use freshwater to reduce NO<sub>x</sub> emissions. Their median blue WF is 354 m<sup>3</sup>/TJ, almost seven times larger than WFs reported by Meldrum et al. [1]. That study, however, excluded water consumption to reduce GHG emissions.

Mekonnen et al. [18] have presented regional estimates of WFs for heat and electricity. Latin America and the Caribbean have an annual average blue WF of 17000 m<sup>3</sup>/TJ<sub>el</sub> for HPPs and 405 m<sup>3</sup>/TJ<sub>el</sub> for TPPs. Our results show that Ecuador's average blue WFs for HPPs and TPPs are 732 m<sup>3</sup>/TJ<sub>el</sub> and 253 m<sup>3</sup>/TJ<sub>el</sub> respectively. The TPPs blue WFs are similar to the value given by Mekonnen et al. [18], but the HPPs blue WF assessed in this study is 23 times smaller than the one calculated by Mekonnen et al. [18]. Ecuadorian large *HFL* power plants have blue WFs ranging from 1200 to 13000 m<sup>3</sup>/TJ<sub>el</sub>. *HFR* and *ROR* HPPs have a blue WF range of 14–4000 m<sup>3</sup>/TJ. Including small HPPs lowered the average blue WF per unit of electricity in Ecuador.

Most of our results are comparable to results of previous studies, which suggest that the methods used, and the assumptions made were logic. However, deviations indicate that earlier estimations based on regional averages and large installations might overestimate the WFs.

The efficient use of freshwater for electricity generation is paramount in a context where electricity demand is increasing, and freshwater resources are becoming scarcer. Our results show that there are opportunities for a more water efficient power generation, not only for Ecuador but probably also for other countries and regions.

## 6. Conclusions

There are large differences among blue WFs of different power plant technologies in Ecuador. These variations can be ascribed to the difference in fuel use, operating conditions, and infrastructure. Electricity from biomass has the largest blue WF (14557–26377 m<sup>3</sup>/TJ<sub>el</sub>), followed by electricity from hydropower (14–13085 m<sup>3</sup>/TJ<sub>el</sub>). Electricity generated in thermal power plants using fossil fuels have WFs between 9 and 936 m<sup>3</sup>/TJ<sub>el</sub>.

The largest blue WF variation occurs in the hydropower plant category where blue WFs mainly depend on the power plant's

infrastructure. Large *dammed flooded lake* hydropower plants have the largest blue WF, small ROR hydropower plants *with reservoirs* the smallest. *Dammed* hydropower plants have larger blue WFs than ROR. However, ROR hydropower plants have a significant blue WF in relation to their electricity output. In the category of TPP's, the subclass of thermal power plants with wet-tower cooling have the largest blue WFs, gas-fired Brayton power plants the smallest. The blue WFs of the power plants with once-through cooling or internal combustion engines with dry-cooling is smaller than power plants with wet-tower cooling. Nonetheless, even though their cooling system does not consume water, their direct blue WF is comparable with other technologies due to the fuel mix they use. Heavy fuels (crude oil, fuel oil, and residue oil) require preheating, which can be water-intensive if it is steam-based. Moreover, diesel-fired Brayton power plants use water for GHG control, which is water-intensive. In terms of fuels, Natural gas is the most water-efficient fuel ( $4.21 \text{ m}^3/\text{TJ}_{\text{th}}$ ), followed by crude oil and derivatives ( $36.4\text{--}83.3 \text{ m}^3/\text{TJ}_{\text{th}}$ ). Biomass is the least efficient ( $4910.8 \text{ m}^3/\text{TJ}_{\text{h}}$ ). Overall, gas-fired power plants have seven times smaller blue WFs than crude oil and crude oil derivatives-fired power plants.

WF variations suggest that there are water-efficient technologies, even for the technologies that were considered water-intensive in previous studies (hydropower). *Run-of-the-river* hydropower plants *with reservoirs* and *dammed flooded river* hydropower plants have relatively small blue WFs per unit of electricity that are in the same order of magnitude as WFs of electricity from thermal power plants. Some subclasses of the *run-of-the-river* hydropower plants and the *stationary internal combustion engines* contribute relatively little to Ecuador's blue WF for electricity. This shows that there are alternatives to optimize the electricity mix from a water-efficiency point of view.

The Ecuadorian electricity generation consumes 86.5 million  $\text{m}^3$  of water yearly or 3.5% of the total blue WF. Hydropower plants consume 66% of the total water for electricity, biomass power plants 23%, and thermal power plants 11%. Technology variation and differences among fuel WFs indicate pathways towards water-efficient electricity mixes.

Besides the benchmark WFs calculated in this study, future studies should also consider spatial and temporal constraints of freshwater availability and competition between users in basins where electricity is generated.

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## Appendix A to G. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wri.2019.100112>.

## References

- [1] J. Meldrum, S. Nettles-Anderson, G. Heath, J. Macknick, Life cycle water use for electricity generation: a review and harmonization of literature estimates, *Environ. Res. Lett.* 8 (2013) 015031, <https://doi.org/10.1088/1748-9326/8/1/015031>.
- [2] E.D. Williams, J.E. Simmons, BP, Water in the Energy Industry: an Introduction, (2013) <http://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/BP-ESC-water-handbook.pdf>.
- [3] IEA, Water-energy nexus, World Energy Outlook 2016, IEA publications, Paris, 2016, p. 48, <https://doi.org/10.1787/weo-2016-11-en>.
- [4] WWAP, The United Nations World Water Development Report 2014: Water and Energy, UNESCO, Paris, 2014.
- [5] P.H. Gleick, Water and energy, *Annu. Rev. Energy Environ.* 19 (1994) 267–299.
- [6] M.M. Mekonnen, A.Y. Hoekstra, The blue water footprint of electricity from hydropower, *Hydrol. Earth Syst. Sci.* 16 (2012) 179–187, <https://doi.org/10.5194/hess-16-179-2012>.
- [7] P.W. Gerbens-Leenes, A.Y. Hoekstra, T. van der Meer, The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply, *Ecol. Econ.* 68 (2009) 1052–1060, <https://doi.org/10.1016/j.ecolecon.2008.07.013>.
- [8] B.P. Walsh, S.N. Murray, D.T.J. O'Sullivan, The water energy nexus, an ISO50001 water case study and the need for a water value system, *Water Resour. Ind* 10 (2015) 15–28, <https://doi.org/10.1016/j.wri.2015.02.001>.
- [9] A.Y. Hoekstra, Water footprint assessment: evolution of a new research field, *Water Resour. Manag.* 31 (2017) 3061–3081, <https://doi.org/10.1007/s11269-017-1618-5>.
- [10] IEA, Water for Energy: is energy becoming a thirstier resource? World Energy Outlook 2012, IEA publications, Paris, 2012, p. 33, <https://doi.org/10.1787/weo-2012-en>.
- [11] J. Macknick, R. Newmark, G. Heath, K.C. Hallett, Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature, *Environ. Res. Lett.* 7 (2012), <https://doi.org/10.1088/1748-9326/7/4/045802>.
- [12] P.W. Gerbens-Leenes, A.Y. Hoekstra, T.H. van der Meer, The water footprint of bioenergy, *Proc. Natl. Acad. Sci.* 106 (2009) 10219–10223, <https://doi.org/10.1073/pnas.0812619106>.
- [13] V. Mathioudakis, P.W. Gerbens-Leenes, T.H. Van der Meer, A.Y. Hoekstra, The water footprint of second-generation bioenergy: a comparison of biomass feedstocks and conversion techniques, *J. Clean. Prod.* 148 (2017) 571–582, <https://doi.org/10.1016/j.jclepro.2017.02.032>.
- [14] V. Pthenakis, H.C. Kim, Life-cycle uses of water in U.S. electricity generation, *Renew. Sustain. Energy Rev.* 14 (2010) 2039–2048, <https://doi.org/10.1016/j.rser.2010.03.008>.
- [15] J. Liu, D. Zhao, P.W. Gerbens-Leenes, D. Guan, China's rising hydropower demand challenges water sector, *Sci. Rep.* 5 (2015) 11446, <https://doi.org/10.1038/srep11446>.
- [16] L. Batan, J.C. Quinn, T.H. Bradley, Analysis of water footprint of a photobioreactor microalgae biofuel production system from blue, green and lifecycle perspectives, *Algal Res* 2 (2013) 196–203, <https://doi.org/10.1016/j.algal.2013.02.003>.
- [17] E.S.S. W.R.M., K.S.G., P.H.K., D.H. Marks, The water consumption of energy production: an international comparison, *Environ. Res. Lett.* 9 (2014) 105002 <http://stacks.iop.org/1748-9326/9/i=10/a=105002>.
- [18] M.M. Mekonnen, P.W. Gerbens-Leenes, A.Y. Hoekstra, The consumptive water footprint of electricity and heat: a global assessment, *Environ. Sci. Water Res. Technol.* 1 (2015) 285–297, <https://doi.org/10.1039/c5ew00026b>.
- [19] M.M. Mekonnen, P.W. Gerbens-Leenes, A.Y. Hoekstra, Future electricity: the challenge of reducing both carbon and water footprint, *Sci. Total Environ.* 569 (2016) 1282–1288, <https://doi.org/10.1016/j.scitotenv.2016.06.204>.



- [20] J. Fulton, H. Cooley, The water footprint of California's energy system, 1990–2012, *Environ. Sci. Technol.* 49 (2015) 3314–3321, <https://doi.org/10.1021/es505034x>.
- [21] T. Okadera, Y. Geng, T. Fujita, H. Dong, Z. Liu, N. Yoshida, T. Kanazawa, Evaluating the water footprint of the energy supply of Liaoning Province, China: a regional input–output analysis approach, *Energy Policy* 78 (2015) 148–157, <https://doi.org/10.1016/j.enpol.2014.12.029>.
- [22] A.Y. Hoekstra, A.K. Chapagain, M.M. Aldaya, M.M. Mekonnen, *The Water Footprint Assessment Manual*, first ed., Earthscan, London, 2011.
- [23] ISO, ISO 14046, 2014 Environmental Management — Water Footprint — Principles, Requirements and Guidelines, (2014).
- [24] IEA, IEA Statistics, <http://www.iea.org/statistics/>, (2017).
- [25] MEER, Balance Energético Nacional 2016, Quito, (2017).
- [26] Food and Agriculture Organization [FAO], AQUASTAT Main Database, (2016).
- [27] A. Briones Hidrovo, J. Uche, A. Martínez-Gracia, Accounting for GHG net reservoir emissions of hydropower in Ecuador, *Renew. Energy* 112 (2017) 209–221, <https://doi.org/10.1016/j.renene.2017.05.047>.
- [28] ARCONEL, Estadística del Sector Eléctrico Ecuatoriano, Quito, (2018) <http://www.regulacionelectrica.gob.ec/estadistica-del-sector-electrico/>.
- [29] D. Egré, J.C. Milewski, The diversity of hydropower projects, *Energy Policy* 30 (2002) 1225–1230, [https://doi.org/10.1016/S0301-4215\(02\)00083-6](https://doi.org/10.1016/S0301-4215(02)00083-6).
- [30] M.A. Sari, M. Badruzzaman, C. Cherchi, M. Swindle, N. Ajami, J.G. Jacangelo, Recent innovations and trends in in-conduit hydropower technologies and their applications in water distribution systems, *J. Environ. Manag.* 228 (2018) 416–428, <https://doi.org/10.1016/j.jenvman.2018.08.078>.
- [31] CELEC EP - Hidronación, Información Técnica, (2018) <https://www.celec.gob.ec/hidronacion/>, Accessed date: 23 June 2018.
- [32] T.H. Diehl, M.A. Harris, J.C. Murphy, S.S. Hutson, D.E. Ladd, Methods for Estimating Water Consumption for Thermoelectric Power Plants in the United States, (2013) <https://doi.org/10.3133/sir20135188>.
- [33] Y.A. Gengel, M.A. Boles, *Thermodynamics: an Engineering Approach*, eighth ed., McGraw-Hill Education, New York, 2014.
- [34] D. Jiang, A. Ramaswami, The “thirsty” water-electricity nexus: field data on the scale and seasonality of thermoelectric power generation's water intensity in China, *Environ. Res. Lett.* 10 (2015), <https://doi.org/10.1088/1748-9326/10/2/024015>.
- [35] U.S. Department of Energy [DOE], *The Water-Energy Nexus: Challenges and Opportunities*, Washington, DC, (2014).
- [36] Olade, Sistema de Información Económica Energética: Energía en Cifras, (2012) <http://www.olade.org/sites/default/files/publicaciones/PLEGABLE2012-SEC.pdf>.
- [37] MICSE, Balance Energético Nacional 2015: Año Base 2014, Quito, 2015, <http://www.sectoresestrategicos.gob.ec/balance-energetico/>.
- [38] B. Challen, R. Baranescu, *Diesel Engine Reference Book*, second ed., Butterworth and Heinemann Publishing, 1999.
- [39] Z. Wang, S. Shi, S. Huang, J. Tang, T. Du, X. Cheng, R. Huang, J.Y. Chen, Effects of water content on evaporation and combustion characteristics of water emulsified diesel spray, *Appl. Energy* 226 (2018) 397–407, <https://doi.org/10.1016/j.apenergy.2018.06.023>.
- [40] A. Gongora, D. Villafranco, Sugarcane bagasse cogeneration in Belize: a review, *Renew. Sustain. Energy Rev.* 96 (2018) 58–63, <https://doi.org/10.1016/J.RSER.2018.07.034>.
- [41] ARCONEL, SISDAT-BI: Reportes de Información Estadística del Sector Eléctrico, Quito, 2019, <http://190.11.14.52:8050/>.
- [42] MAGAP, Boletín Situacional Caña de Azúcar: 2016, Quito, (2016) <http://sipaa.agricultura.gob.ec>.
- [43] D. Gewald, K. Siokos, S. Karellas, H. Spliethoff, Waste heat recovery from a landfill gas-fired power plant, *Renew. Sustain. Energy Rev.* 16 (2012) 1779–1789, <https://doi.org/10.1016/j.rser.2012.01.036>.
- [44] A.-M. Boulay, A.Y. Hoekstra, S. Vionnet, Complementarities of water-focused life cycle assessment and water footprint assessment, *Environ. Sci. Technol.* 47 (2013) 11926–11927, <https://doi.org/10.1021/es403928f>.
- [45] S. Pfister, A.-M. Boulay, M. Berger, M. Hadjikakou, M. Motoshita, T. Hess, B. Ridoutt, J. Weinzettel, L. Scherer, P. Döll, A. Manzardo, M. Núñez, F. Verones, S. Humbert, K. Buxmann, K. Harding, L. Benini, T. Oki, M. Finkbeiner, A. Henderson, Understanding the LCA and ISO water footprint: a response to Hoekstra (2016) “A critique on the water-scarcity weighted water footprint in LCA,” *Ecol. Indic.* 72 (2017) 352–359, <https://doi.org/10.1016/j.ecolind.2016.07.051>.
- [46] R.J. Hogeboom, L. Knook, A.Y. Hoekstra, The blue water footprint of the world's artificial reservoirs for hydroelectricity, irrigation, residential and industrial water supply, flood protection, fishing and recreation, *Adv. Water Resour.* 113 (2018) 285–294, <https://doi.org/10.1016/j.advwatres.2018.01.028>.
- [47] ARCONEL, GeoPortal del Arconel V2.5.1.5, (2016) <http://geoportal.regulacionelectrica.gob.ec/visor/index.html>.
- [48] E.P. Petroecuador, Informe Estadístico 2013, Quito, (2014).
- [49] ARCH, Boletín Estadístico 2016, Quito, (2017).
- [50] E.P. Petroamazonas, Memoria de Sostenibilidad 2013, (2014) [http://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2014/12/MEMORIA\\_SOSTENIBILIDAD\\_PETROAMAZONAS\\_2013.pdf](http://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2014/12/MEMORIA_SOSTENIBILIDAD_PETROAMAZONAS_2013.pdf).
- [51] M. Wu, M. Mintz, M. Wang, S. Arora, Water consumption in the production of ethanol and petroleum gasoline, *Environ. Manag.* 44 (2009) 981–997, <https://doi.org/10.1007/s00267-009-9370-0>.
- [52] E.P. Petroecuador, Memoria de Sostenibilidad Refinería Esmeraldas, Quito, (2013) <http://www.eppetroecuador.ec/wp-content/uploads/downloads/2015/03/Memoria-de-sostenibilidad-Refineria-Esmeraldas.pdf>, Accessed date: 25 May 2017.
- [53] S.A. Sociedad Agrícola e Industrial San Carlos, Memoria Sostenibilidad 2016, Guayaquil, 2016, <http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/memoria-sostenibilidad-2016.pdf>.
- [54] S.A. Azucarera Valdez, Memoria de Sostenibilidad 2016, Unidad de Negocio Agroindustrial, 2017, <http://www.azucaravaldez.com/pdf/Memoria-de-Sostenibilidad-2016-Unidad-Agroindustrial.pdf>.
- [55] S.A. Sociedad Agrícola e Industrial San Carlos, Balance Social 2012, Guayaquil, 2012, [http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/balance\\_social\\_2012.pdf](http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/balance_social_2012.pdf).
- [56] S.A. Sociedad Agrícola e Industrial San Carlos, Balance Social 2013, Guayaquil, 2013, [http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/balance\\_social\\_2013.pdf](http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/balance_social_2013.pdf).
- [57] S.A. Sociedad Agrícola e Industrial San Carlos, Balance Social 2014, Guayaquil, 2014, [http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/balance\\_social\\_2014.pdf](http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/balance_social_2014.pdf).
- [58] S.A. Sociedad Agrícola e Industrial San Carlos, Memoria de sostenibilidad 2017, Guayaquil, 2017, <http://www.sancarlos.com.ec/portal/html/themes/ingenio/pdf/memoria-sostenibilidad-2017.pdf>.
- [59] S.A. Azucarera Valdez, Memoria de sostenibilidad 2015: Unidad de Negocio Agroindustrial, Guayaquil, 2015, <https://issuu.com/innobis.memorias/docs/valdez-memoria-de-sostenibilidad-2015>.
- [60] S.A. Azucarera Valdez, Memoria de sostenibilidad 2014: Unidad de Negocio Agroindustrial, Guayaquil, 2014, [https://issuu.com/fundacionnobis/docs/memoria-de-sostenibilidad\\_2014\\_unid](https://issuu.com/fundacionnobis/docs/memoria-de-sostenibilidad_2014_unid).
- [61] O. Núñez, E. Spaans, Afinación del balance hídrico para programación de riegos en el ingenio San Carlos, *Cart. Inf* 11 (2009) 4–9.
- [62] M.R.L.V. Leal, A.S. Walter, J.E.A. Seabra, Sugarcane as an energy source, *Biomass Convers. Biorefinery.* 3 (2013) 17–26, <https://doi.org/10.1007/s13399-012-0055-1>.
- [63] T.L. Tew, R.M. Cobill, Genetic improvement of sugarcane (*saccharum* spp.) as an energy crop, *Genet. Improv. Bioenergy Crop*, Springer New York, New York, NY, 2008, pp. 273–294, [https://doi.org/10.1007/978-0-387-70805-8\\_9](https://doi.org/10.1007/978-0-387-70805-8_9).
- [64] G.R. Harwell, Evaluation of Evaporation from Open Water - A Review of Selected Studies, Summary of U.S. Army Corps of Engineers Data Collection and Methods, and Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas, Denver, Colorado, (2012) <http://www.usgs.gov/>.
- [65] INAMHI, Meteorología (2018), <http://www.serviciometeorologico.gob.ec/>, Accessed date: 4 May 2018.
- [66] CONELEC, Atlas solar del Ecuador, Quito, 2008, [http://www.conelec.gob.ec/archivos\\_articulo/Atlas.pdf](http://www.conelec.gob.ec/archivos_articulo/Atlas.pdf).
- [67] IGM, Cartografía Básica Oficial, (2018) <http://www.igm.gob.ec/index.php/en/servicios/productos-cartograficos-on-line>.
- [68] D. Zhao, J. Liu, A new approach to assessing the water footprint of hydroelectric power based on allocation of water footprints among reservoir ecosystem services, *Phys. Chem. Earth, Parts A/B/C* 79–82 (2015) 40–46, <https://doi.org/10.1016/j.pce.2015.03.005>.
- [69] P.W. Gerbens-Leenes, A.Y. Hoekstra, T.H. van der Meer, Water footprint of bio-energy and other primary energy carriers, *Value* 29 (2008) 44.

- [70] M.M. Mekonnen, A.Y. Hoekstra, National water footprint accounts, Unesco - Ihe. 1 (2011) 80, <https://doi.org/10.5194/hessd-8-763-2011>.
- [71] ARCONEL, *Inventario De Recursos Energéticos Del Ecuador Con Fines De Producción Eléctrica – 2015*, Quito, (2015).
- [72] P.W. Gerbens-Leenes, A.Y. Hoekstra, R. Bosman, The blue and grey water footprint of construction materials: steel, cement and glass, *Water Resour. Ind.* 19 (2018) 1–12, <https://doi.org/10.1016/j.wri.2017.11.002>.
- [73] M.M. Mekonnen, A.Y. Hoekstra, The green, blue and grey water footprint of crops and derived crop products, *Hydrol. Earth Syst. Sci.* 15 (2011) 1577–1600, <https://doi.org/10.5194/hess-15-1577-2011>.
- [74] FAO, *Statistics*, (2018).
- [75] ARCONEL, *Estadística anual y multianual del sector eléctrico ecuatoriano 2016*, Quito, 2017, <http://www.regulacionelectrica.gob.ec/wp-content/uploads/downloads/2017/08/Estadística-anual-y-multianual-sector-eléctrico-2016.pdf>.

## Glossary

*BPP*: Biomass power plant  
*CWR*: Crop Water Requirement  
*GHG*: Greenhouse Gas  
*Gross electricity output/generation*: Total electricity generated by the power plant before any use  
*HPP*: Hydropower plant  
*ICE*: Internal Combustion Engine thermal power plant  
 $m^3/m_j^3$ : cubic meter of freshwater per cubic meter of fuel  
 $m^3/t$ : cubic meter of fresh water per ton of biomass  
*NOx*: Nitrous oxide  
*OPP*: Other renewables, power plant (which include solar plants and wind farms)  
*PP*: Powerplant  
*ROR*: Run-of-the-river  
*TJ<sub>el</sub>*: Terajoule electric  
*TJ<sub>th</sub>*: Terajoule of thermal energy  
*TPP*: Thermal Power Plant  
*USD*: United States Dollars  
*WF*: Water Footprint  
*WFA*: Water Footprint Assessment